HEAT TRANSFER CORRELATION FOR GLYCEROL SOLUTIONS IN AGITATED THIN FILM EVAPORATOR

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By
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CHE-1979-M-KAK-HEA

TO

MY PARENTS

CERTIFICATE

This is to certify that this work 'HEAT TRANSFER CORRELATION FOR GLYCEROL SOLUTIONS IN AGITATED THIN FILM EVAPORATOR' has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Influence of feed rate (100-1300 kg/h m^2), overall temperature difference (10-50°C), rotor speed (500-1600 rev/min) and heat flux ($4 \times 10^4 - 30 \times 10^4$ kJ/h m^2) on heat transfer coefficient for water and glycerol solutions (40 and 65 per cent) was studied in an agitated thin film evaporator (Votator model 04-012, Laboratory Turba Film Processor). Experimental results are correlated according to the following expression:

$$Nu = 0.29\, Re^{0.39}\; Re'^{0.13}\; Pr^{0.25}$$

where,

Nu = Nusselt number,

Re = Flow Reynolds number

Re' = Rotary Reynolds number

and Pr = Prandtl number

The experiments covered the following range of dimensionless numbers, Re = 50-1500, $Re' = 1 \times 10^4 - 17 \times 10^4$ and Pr = 1.8 - 15.5, Nu = 5-27.

NOMENCLATURE

A	Heat transfer area of evaporator, m^2
A_i	Inside heat transfer area of evaporator, m^2
A_o	Outside heat transfer area of evaporator, m^2
C	Constant in correlation
C_p	Specific heat, Kcal/kg K
D	Inside diameter of evaporator, m
D_e	Equivalent diameter, m
D_o	Outside diameter of evaporator, m
E	Rate of evaporation, kg/h m^2
F	Feed rate, kg/h m^2
g	Acceleration due to gravity, m/s^2
h_i	Liquid film heat transfer coefficient, kW/m^2K
h_s	Steam side film heat transfer coefficient, kW/m^2K
k	Thermal conductivity of liquid, kW/mK
K_1	Constant
k_f	Thermal conductivity of steam condensate film, kW/mK
k_w	Thermal conductivity of metal wall, kW/m K
N	Rotor speed, rev/min
N'	Rotor speed, rad/h
n_B	Number of blades on rotor
P	Product rate, kg/h m^2
Q	Heat flux, kJ/h m^2
r_h	Hydraulic radius, m

S	Mass rate of flow of steam condensate per unit length of perimeter, kg/h m
T_f	Feed temperature, ^oC
T_p	Product temperature, ^oC
T_s	Steam temperature, ^oC
ΔT	Overall temperature difference, ^oC
U	Overall heat transfer coefficient, kW/m^2K
x_w	Thickness of metal wall of evaporator, m

DIMENSIONLESS NUMBERS

Nu	Nusselt number $= h_i D_e/k$
Pr	Prandtl number $= C_p \mu/k$
Re	Flow Reynolds number $= 4 \tau/\mu$
Re'	Rotary Reynolds number $= DD_e N' \rho /\mu$

GREEK LETTERS

μ	Viscosity, kg/h m
μ_f	Viscosity of steam condensate film, kg/h m
ρ	Density of liquid, kg/m^3
ρ_f	Density of steam condensate film, kg/m^3
λ_s	Latent heat of condensation of steam, kcal/kg
τ	Mass rate of flow of liquid per unit length of perime kg/m h
δ	Blade tip clearance, m
γ	Rate of shear, s^{-1}

EXPONENTS

a	Exponent of Re
b	Exponent of Re'
c	Exponent of Pr

CHAPTER 1

INTRODUCTION

Agitated thin film evaporators (ATFE) are used for the concentration of heat sensitive liquors and viscous solutions in the food, pharmaceutical and chemical process industries. Typical examples of applications of ATFE include the following: ammonium nitrate, ascorbic acid, candy mix, chocolate mix, coffee extract, dyes, fruit juices and pulp, gelatine, glycerine, SBR latex, insulin, insecticides, jams, jellies, lactic acid, plastic emulsions, PVC latex, sugar syrups, urea, vitamins, vinyl acetate, etc.

Considerable decrease in the process liquid film resistance to heat transfer is accomplished in ATFE by the mechanically induced turbulence in the liquid film by a central rotar equipped with blades. Residence time of the process liquor in ATFE is short and narrow (3 to 10 seconds) and the heat transfer coefficient and evaporation ratio are normally high. The influence of rotor agitation gives a uniform undergraded product by eliminating dry spots which may otherwise form in conventional climbing/falling film units due to inadequate flow, high viscosity, non-uniform wetting and channelling with possible overheating and buildup of product as a scale on the heat transfer surface. Foam

problems are also eliminated in agitated thin film processing units. ATFE units are especially suitable for processing of liquids of low thermal conductivity like fatty acids, glycerine, ethanolamines etc. where turbulence produced at high rotor speeds decreases the effective liquid film thickness controlling heat transfer.

Major contributions to the published literature on agitated thin film processing equipment comes mainly from machinery suppliers like Luwa, Chemetron, Rodney Hunt, Pfaudler, Kontro advocating the use of thin film concept for the evaporation of heat sensitive and/or viscous liquors, with some data to support their claims on equipment capabilitie Much of the development work by the various organizations being of a proprietary nature, there are fewer references reporting detailed results of laboratory or pilot plant investigations. The diverse range of process applications given earlier shows that in majority of cases the process liquor tends to be non-Newtonian in nature. Study of the heat transfer phenomenon in ATFE for such systems is necessarily complicated. due to a lack of knowledge of the non-Newtonian features. Heat transfer in simple systems (Newtonian) are relatively easily studied and forms the subject of this investigation.

A laboratory ATFE unit (Votator model 04-012 laboratory Turba film processor) is used in this study. Systems studied include water and glycerol solutions (40 and 65 per cent glycerol). Heat transfer coefficient for the process fluid was determined for a range of feed rates, rotor speed and overall thermal driving force for constant rotor configurations (number of blades and blade tip clearance).

CHAPTER 2

REVIEW OF PREVIOUS WORK

2.1 Agitated Thin Film Processing Technology:

Salient features of thin liquid film processors include very short residence time, high heat and mass transfer rates and ability to process highly viscous products. Some of the earliest applications are mainly as a scraped surface heat exchanger in processing food products and in the last two decades it is widely used for concentrating heat sensitive and/or viscous products in an agitated thin film evaporator. In recent years agitated thin film processors have been modified to suit other mass transfer operations like distillation, fractionation, stripping, absorption, drying and also for chemical reactions involving large heat effects and polymerisation reactions. Agitated thin film processors in all these applications usually have 2 to 6 blades attached to a central rotor and designed for either scraping or wiping action. These blades are fixed rigidly to the shaft to maintain a fixed clearance between the blade tip and the tube wall. The blades can also be hinged to the shaft and pressed against the wall due to centrifugal force during shaft rotation. There are several proprietory rotor blade configurations and selection often is based upon the physico-chemical characteristics of

the liquor system and hydrodynamics of film flow where the rotor blade action provides a high rate of surface renewal permitting high rates of heat and mass transfer. In some applications feed is introduced as a liquid and product withdrawn as a powder at the bottom and the rotor blade configuration and design are varied from top to bottom to handle the changing liquor-slurry-solid system in single pass operation through the same unit. Luwa Corp. of Switzerland is probably a pioneer in the various developments of agitated thin-film processing technology for a large number of commercial systems and processes. In spite of the above technical advances, there are only few reports of detailed laboratory investigations relating to the application of thin film processes for evaporation of simple systems like water [5, 7, 8,10,12,16], glycerol solution [5, 18], sugar solution [16, 20], toluene [20, 34] and ethanol [10, 20]. The results of these investigations are discussed in a subsequent section. Reports on commercial applications of ATFE include systems like SBR latex [2], copolymer of acrylonitrile and vinyl acetate in dimethyl - pharmamide (650 to 750 cp)[14], alkyloamides [24], urea [31] and food products like coffee extract, candy mix, gelatine, fruit juice, edible oils and tomato paste [8] and corn syrup, peach, pear and apricot [26].

2.2 Description of ATFE Unit:

General features of ATFE units are summarised in Table 2.1 and a schematic sketch is given in Figure 2.1. Commercial units are available in sizes upto 40 m^2 (upto 2 m diameter and 10 m length) limited by mechanical constraints of fabrication, rotor and blade design and alignment, rotor scale and thickness of walls. ATFE units are used generally in the vertical position though some manufacturers have adopted the horizontal design. The blades normally have a straight or tapered edge to give fixed or variable clearance which also can be obtained by blades which are either fixed or hinged to the shaft respectively. The unit is equipped with a top or bottom rotor drive and generally has an external condenser. An exception to this is the design by Pfaudler which has an internal condenser arrangement. This is also adopted by Dalal Engg. Co., Bombay who are the sole manufacturers of ATFE units in this country since 1975. Mutzenberg [25], Parker [28] and Fischer [12] have reviewed the status of thin film processing technology discussing the equipment types, process applications and relative economics.

2.3 Hydrodynamics of Agitated Thin Film:

The unique feature of ATFE is the turbulence induced in the thin liquid film by the rotor for producing and maintaining the film. The agitation of thin film permits the

TABLE 2.1

GENERAL FEATURES OF ATFE UNITS

1. Heat transfer area, m^2	: 0.1-24 m^2 (1-250 ft^2)
2. Capacity, kcal/hm^2	: Aqueous 165000 (60000 Btu/h ft^2) Organic 27000-82000 (10,000 - 30000 Btu/h ft^2)
3. Liquor throughput	: 1500 kg/h m^2 (upto 300 lb/h ft^2)
4. Pressure, mm Hg	: 1-760 (vacuum) (Positive pressure application possible)
5. Pressure drop, mm Hg	: 0.5
6. Heating media	: Steam, hot oil, dowtherm
7. Evaporation ratio (maximum)	: 100:1
8. Residence time, s	3-10 (normal) 3-100 (with special devices)
9. Viscosity, cp (maximum)	: 300,000
10. Overall U (range)	: 1-3 kW/m^2K (150-500 Btu/h ft^2 ^oF)
11. Material of construction	: SS, MS, Aluminium, Copper, Alloys, SS clad
12. Rotor configuration	: Straight/tapered fixed/hinged spring loaded special designs (Proprietory)
13. Blade clearance, mm	: 0.75-2.5 (0.03 - 0.1 in)
14. Blade tip velocity, m/s	
Scraping action	: 1.5 - 3.0 (5-10 f/s)
Wiping action	: 9 -12 (30-40 f/s)

Table 2.1 (contd)

15.	Condenser	: Mostly external to unit (Internal possible)
16.	Rotor drive	: Top/bottom
17.	Separator	: Integral/separate
18.	Botton bearing	: External/Internal/none
19.	Vapor-liquid flow	: Cocurrent/countercurrent
20.	Film flow	: Falling vertical film Horizontal film Vertical climbing film (none commercial yet)
21.	Unit:	: Horizontal/vertical

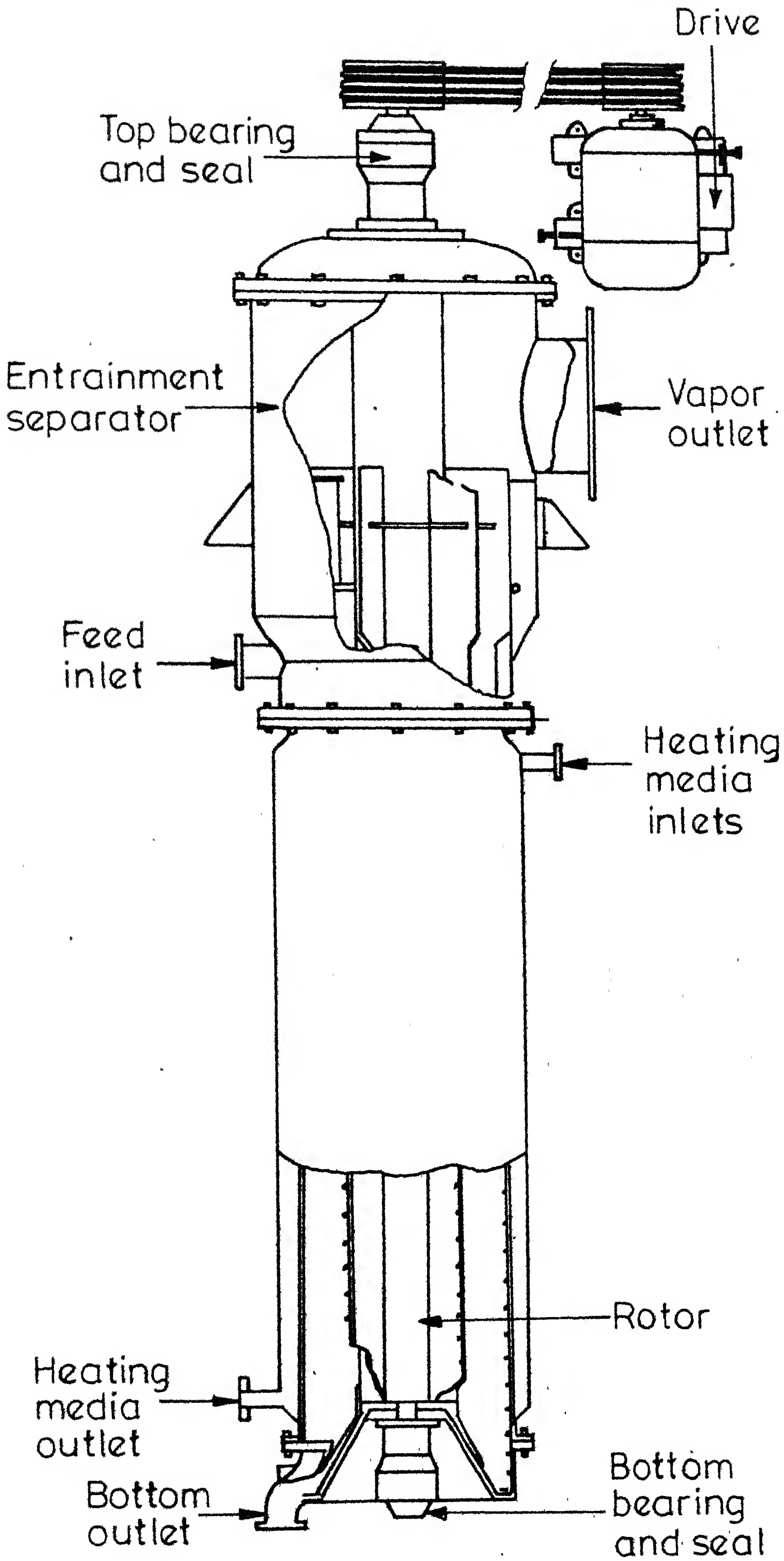

Fig. 2.1 – Sketch of agitated thin film evaporator.

processing of high viscosity liquids (upto 3,00,000 cp at low shear rates) and liquids with suspended solids. The liquid flow patterns in ATFE are complex as compared to conventional climbing/falling film evaporators. The liquid flow pattern and residence time distribution in ATFE are described by Mutzenberg [25]. The blade rotating at a velocity of 5 - 15 m/s pushes a bow wave having a zone length determined by the physical properties and the vertical flow rate of the liquor. Adjacent to the bow wave is a highly turbulent squeeze zone followed by tranquilizing zone. The same cycle is repeated by the next blade. An exact calculation of the bow wave profile and magnitude depends upon many factors like viscosity, liquor throughput etc. and is difficult to analyse. Mutzenberg [25] has reported the bow wave zone lengths of the order of 2.5 to 10 cms for ATFE.

The flow of the liquid in ATFE is caused by the rotation of agitator and the vertical gravitational flow down the wall. Thus liquid executes both vertical and tangential flows. For high viscosities the tangential velocity is higher than the vertical flow velocities. The vertical flow is determined by gravitational and viscous forces. The viscous forces vary along the flow length as the product viscosity changes with concentration and temperature along the tube length. For high viscosities the vertical flow velocity is low. Tangential flow is produced when the liquid film thickness is greater

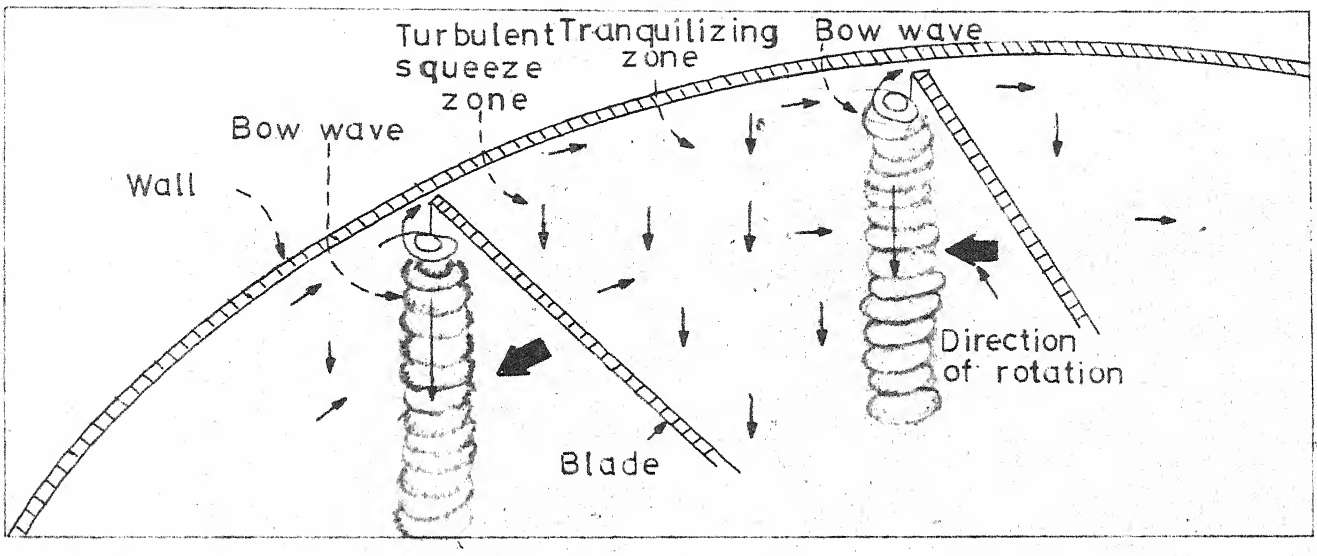

Fig. 2·2 Flow Patterns in Agitated Thin Film Processor (Mutzenberg)

than the blade tip clearance. Godau [13] and Kern and Karakas[19] have given a detailed discussion on the flow patterns in ATFE. Kern and Karakas described the bow wave as a fillet of liquid which is driven around the periphery of the rotor by the rotor blade. The fillet exchanges heat and mass with the surrounding liquid and prevents the accumulation of a liquid film resistant to heat and mass transfer. The liquid film resistance becomes smaller with a decrease in clearance between the blade tip and the wall. Kern and Karakas [19] have described a mathematical model for bow wave analysis by assuming that the free liquid surface of the bow wave forms an angle of 45° with the rotor blade. According to this, a calculation can be carried out over the cross-section, assuming that the liquor runs downwards in laminar flow. Kern and Karakas [19] have developed design equations for agitated thin film equipment based on heat, mass and momentum balance and have solved for the held up and power consumption in ATFE for the condition of laminar flow. They assumed that liquid film thickness is constant and equal to blade tip clearance. The derivation include the Newtonian or non-Newtonian nature of process liquor and fixed or hydrodynamic blades. This is the only theoretical analysis on agitated thin film processing so far and can be used as a basis for further theoretical investigations on agitated thin film technology.

2.3.1 Average Film Thickness:

The liquid film thickness is determined by the physical properties of the medium, the gravitational force and the liquid flow rate. Godau [13] and Domanski [11] have developed expressions for the liquid film thickness in ATFE. Godau [13] solved the Navier stokes equation for vertical flow of agitated thin film and obtained an exact and an approximate solution for the liquid film thickness assuming the constant viscosity of liquid.

$$\delta = \left[\frac{0.75\ \mu^2\ Re}{\rho^2\ g} \right]^{1/3} \tag{2.1}$$

Domanski [11] has derived the following expression equation (2.2) for the average film thickness of water and glycerol solutions in an agitated thin film unit under isothermal operation and obtained $\pm$ 15 per cent agreement with experimental data from a laboratory unit

$$\frac{\delta}{R} = \frac{\varepsilon \Delta}{R} + C\ n_B^{0.29}\ K_N^{0.14} \left(\frac{\Gamma - \Gamma_1}{\rho \nu}\right)^{0.57}\ Fr_c^{0.57}\ Re_c^{-0.72} \tag{2.2}$$

where δ = average film thickness, mm

R = internal radius of tube

Δ = Blade tip clearance

n_B = number of rotor blades

Γ = liquid rate over the cylindrical surface

Γ_1 = liquid rate in the layer behind rotor blades

C = 0.35

$Fr_c = W^2R/g$

$Re_c = WR^2/$

W = Angular velocity of rotor

K_N = Power number

P = shaft power

Domanskii's equation can be used to calculate the average residence of the process solution in the ATFE unit and also for the analysis of heat transfer steps.

2.3.2 The Influence of Viscosity on Liquid Flow:

ATFE units are used for high viscous liquids (upto 300,000 cp) and they are usually non-Newtonian for which viscosity is dependent upon shear rate. In conventional evaporators it is not possible to process highly viscous systems but in ATFE they can be processed at high heat transfer rates due to a large decrease in viscosity (some times by a factor of 100) owing to high shear rates (10^3 to 10^4 s^{-1}) prevailing in agitated thin film processors.

Kern and Karakas [19] have given an account of vital role of viscosity in the operation of agitated thin film processors. Viscosity can be expressed by the equation (2.3)

$$\mu = \tau_1/\gamma \tag{2.3}$$

Variation of viscosity with rate of shear can be expressed by

$$\mu = \mu_1 \gamma^{n'-1} \tag{2.4}$$

where μ_1 is the viscosity at unit rate of shear and n' is a flow behaviour index, being unity for Newtonian fluids and less than unity for most non-Newtonians. The shear rate in an agitated thin film processor can be estimated by dividing the linear blade velocity u by the clearance δ. The shear rate of 10,000 s^{-1} can be obtained with 10 m/s blade velocity and 1 mm blade tip clearance.

2.4 Heat Transfer in ATFE:

Heat transfer in ATFE takes place mainly by conduction through a series of resistances contributed by a film of heating medium, heat transfer wall and the process liquid film. In conventional climbing or falling film type of evaporators, the major resistance to heat transfer is caused by the film of the process liquor. Considerable decrease in the process liquid film resistance to heat transfer can be accomplished by mechanically induced turbulence in the film by a central rotor equipped with blades. Typical values of the resistances observed in a climbing film evaporator and agitated thin film evaporator are given in Table 2.2.

TABLE 2.2

RELATIVE HEAT TRANSFER RESISTANCES IN FILM EVAPORATORS

Resistance	Climbing film unit	Agitated falling film unit SS Wall	MS Wall
R_i	56	18	28
R_d	30	-	-
R_w	4	58	34
R_o	10	24	38
R	100	100	100

R_i = Resistance of process liquid film

R_d = Resistance of scale deposits

R_w = Resistance of heat transfer wall

R_o = Resistance of condensing steam film

The action of the rotor decreases the inside film resistance ($R_{\ }$) to less than one third of the overall resistance and the resistance of the heat transfer wall (R_w) could become dominant depending upon material of construction. Wall thickness is normally fixed by fabrication specifications and flexibility is available only in the choice of material (nickel, M.S., SS) of high thermal conductivity compatible with the process liquor and operating conditions. The resistance of the heating medium (R_o) depends upon the nature of the fluid (steam, hot oil, downtherm etc.). R_o can be improved by external surface modifications such as helical grooves or spiral baffles for liquid media and by promoting dropwise condensation of vapors. Many of the commercial process liquors are non-Newtonian in the high concentration range and properties like viscosity, thermal conductivity and specific heat will be important in controlling the liquid film heat transfer coefficient. Resistance of scale deposits is essentially eliminated. By decreasing the inside film resistance to heat transfer, the agitated thin film evaporators can process high viscosity solutions and slurries.

2.5 Review of Heat Transfer Studies in ATFE Units:

Experimental studies on ATFE have been reported by Reay[30], Hauschild [16], Godau [14], Bott and Sheikh [5], Gudheim and Donovan [15], Jones [18], Dieter [10] and

Kirschbaum and Dieter [20]. In all these investigations, the main objective has been to ascertain the variations in overall heat transfer coefficient for the following operating variables: liquor rate, temperature difference, rotor speed, number of rotor blades, viscosity, heat flux and evaporation ratio. Borg and coworkers [2] have reported the overall heat transfer values for pilot plant ATFE units used for the concentration of SBR latex from 40 to 60 per cent solids while Coston [8] and Najder [26] report overall heat transfer values for the concentration of food products (including non-Newtonian Systems). A summary of the salient features of the various laboratory/ pilot plant studies on ATFE units is given in Table 2-3. Babos and Ujhidy [1] have studied the influence of feed rate on the heat transfer coefficient for diazotisation of aniline in ATFE. Borg, Provost and Bawn [2] have studied the concentration of SBR latex from 40 to 60 per cent solids in a pilot agitated film evaporator and obtained overall heat transfer values of 1.25 to 1.75 kW/m^2K. Bott and Sheikh [5] have studied the effect of rotor speed, feed rate and number of blades for evaporation of glycerol solutions and predicted a correlation for the heat transfer coefficient. Coston [8] has advocated the use of agitated thin film evaporators instead of conventional film evaporators or other units (batch operated) for the concentration of food products like coffee extract, candy mix, whole egg, chocolate mix, tomato paste, fruit juices,

TABLE 2.3

SUMMARY OF EXPERIMENTAL WORK ON AGITATED THIN FILM EVAPORATOR

Author	Equipment	Type of agitator	n_B	System	Variables	Results
1	2	3	4	5	6	7
1. Babos and Ujhidy[1]	ATFE 1. D=53.3 mm $A=0.578 m^2$ $\delta=0.5$ mm 2. D=80 mm $A=0.126\ m^2$ $\delta=0.5$ mm	Fixed and hinged	-	Diazotisation of aniline	F	U dependent upon F.
2. Borg, Provost and Bawn[2]	ATFE D=0.3 m $A=0.84\ m^2$ $\delta=0.8$mm SS Wall	Fixed	4	SBR latex	N, per cent solids	$U=1.25-1.75\ kW/m^2K$
3. Bott and Sheikh[5]	ATFE D=38 mm L=0.457 m	Hinged	2-8	Water glycerol	N, F, n_B, T	U is dependent on T. Correlation for evaporation of glycerol solutions.
4. Coston [8]	ATFE $A=0.84\ m^2$	-	-	Coffee extract candy mix, gelatine, whole egg, Fruit juices, edible oils, Tomato paste	-	$U=0.5 -2\ kW/m^2K$

Table 2.3 (contd)

1	2	3	4	5	6	7
5. Dieter[10]	ATFE D=100 mm L=970 mm Copper tube 7mm thick Luwa and Sambay types	Fixed and hinged	3,4	Water Ethanol salt solutions	N, ΔT, μ, k, C_p, T_s	h_i decreased as T_s decreased. ΔT hadonly slight effect on h_i.
6. Godau[14]	ATFE A=0.125 m^2	-	-	Copolymer of acrylonitrile and vinyl acetate in dimethyl formamide (μ=650-750 cp)	F, n_B, δ	Influence of variables on U
7. Gudheim and Donovan[15]	Vertical Straight and tapered (reverse) horizontal unit.	Fixed	-	Water Guar gum	ΔT, F, T_s, μ	T and F had minor effect on U in the reverse taper unit. Influence of viscosity upto 40,000 cp
8. Hauschild [16]	ATFE Luwa unit A=0.8 m^2	-	-	Water Sugar solution	F, ΔT, N, μ	Influence of variables on U.
9. Kern and Karakas [19]	ATFE	-	-	-	-	Theoretical analysis of thin film processor with fixed and hydrodynamically balanced blades. Expression for hold up and power requirement in ATFE. The theory is not checked with experimental data.

Table 2.3(contd)

1	2	3	4	5	6	7
10. Kirschbaum and Dieter [20]	ATFE D=100 mm L=970 mm	Hinged	3	Water ethanol Toluene Sugar solution	N, F, ΔT, μ, C_p, k	ΔT has no effect on U except at higher T and lower F.
11. Jepson[17]	Polymer extruder	-	-	Polymer melt	-	Temperature profile across the film adjacent to heat transfer surface and prediction of heat transfer rates.
12. Leniger and Veldstra[22]	Luwa unit D=60 mm L=490 mm $A=0.954 m^2$ N=1010, 1470, 2120 rev/min δ=1-1.5 mm	Fixed	-	Water	N, F, ΔT, T_s	ΔT had slight effect on U.
13. Monick[24]	ATFE as reactor	Fixed	-	Alkylo amides	-	Relative reaction rates in batch and agitated thin film units for making lauric diethanolamide from methyl laurate and diethanolamine Residence time 103 Vs 2-6h and 90 vs 60 per cent conversion in continuous and batch operation.
14. Najder[26]	ATFE	-	-	Corn syrup Peach Pear Apricot Water	μ	General discussion of equipment capabilities

Table 2.3 (contd)

1	2	3	4	5	6	7
15. Osipow[27]	ATFE Pilot plant unit	-	-	Sucrose fatty acid monoester	-	ATFE used for separation of methanol(and some solvent)from sugar ester to (surfactant) reduce batch time.
16. Rea[illegible] [30]	Luwa unit	Fixed	-	Water toluene (MC solutions)	N, F, μ, δ	U increases as δ is reduced. U increases with F upto a critical value.
17. Reed and-Reynolds[31]	ATFE	-	-	Urea	-	Concentration of 80 per cent to 99.5 per cent urea to eliminatebiuret formation (less than 0.1 per cent)
18. Schneider [33]	ATFE Luwa and Sambay units	Hinged	4	10 per cent glycerol solution	ΔT	Mean film thickness and residence time is measured as functions of F and μ.
19. Skocylas [34]	Sambay unit	Hinged	-	Water,methanol, ethylene glycol, toluene	N, c_p, μ, k, F	Correlation for h_i is given.

james and jellies and deodorization and refining of edible oils. Dieter [10] has studied the influence of rotor speed, viscosity, head load, product concentration, temperature difference on heat transfer rates for water, ethanol and salt solution. Luwa unit used by Dieter had fixed rotor blades and Sambay unit was provided with hinged blades. Godau [14] has studied the influence of feed rate, number of blades [3, 4 and 5] and clearance (0.6, 1, 1.5 mm) on the heat transfer coefficient for a copolymer of acrylonitrile and vinyl acetate in dimethylformamide (viscosity 650-750 cp) in a laboratory Luwa type unit, and the results show an increase in heat transfer coefficient with decrease in blade tip clearance, increase in rotor speed and increase in feed rate.

Gudheim and Donovan [15] give comparative performance results of units with vertical straight blades and horizontal (reverse) taper blades for evaporation of water. The authors claim the superiority of the horizontal unit with regard to heat flux, variable clearance, residence time and evaporation ratio. Hauschild's [16] results in a laboratory Luwa unit for water and sugar solution show the effects of throughput, temperature difference, rotor speed and viscosity on overall heat transfer coefficient. Kern and Karakas [19] have developed a theoretical analysis of agitated thin film processor with fixed and hydrodynamically balanced blade and gave an expression for the power requirement. The theory is not checked with experimental data.

Kirschbaum and Dieter [20] have studied the influence of feed rate, rotor speed, temperature difference and viscosity on heat transfer coefficient for water, ethanol and sugar solution. They concluded that temperature difference had no effect on overall heat transfer coefficient except at higher temperature difference and lower feed rates. Jepson [17] has predicted the heat transfer rates for polymer melt in a polymer extruder. Leniger and Veldstra [22] have studied the effects of rotor speed, feed rate and temperature difference for evaporation of water in a Luwa unit with fixed blades and found that temperature difference had slight effect on overall heat transfer coefficient. Monick [24] has recommended a turbulent film evaporator to be used as a reactor for making alkylolamides; for example, residence time of 10 s vs 2-6 h and conversion of 90 per cent vs 60 per cent was obtained during continuous and batch processes respectively, for making lauric diethanalamide from methyl laurate and diethanolamine. Najder [26] gave a general discussion on the capabilities of agitated thin film equipment for processing food products. Osipow [27] has studied the agitated thin film processing for separation of methanol from sugar ester to reduce batch time. Reay [30] has reported on the influence of blade clearance, feed rate, heat flux and rotor speed on the overall heat transfer coefficient for water in a Luwa unit; heat transfer coefficient increases with a decrease in blade tip

clearance and increase in feed rate upto a critical level. The effect of rotor speed (800-3200 rev/min) an overall heat transfer coefficient was rather small. Reed and Reynolds [31] report plant experience in reduced biurret formation (less than 0.1 per cent) during concentration of urea from 80 to 99.5 per cent in ATFE. Schreider [33] has studied the mean film thickness and residence time as functions of feed rate and viscosity for 10 per cent glycerol solution in Luwa and Sambay units. Skocylas [34] has reviewed the features of various agitated thin film units and has proposed a correlation for heat transfer coefficient for water and ethylene glycol systems in Sambay unit with hinged blades.

Based on the above review of the results of the various investigators, the following general trends in behaviour of ATFE units can be inferred.

1. Overall heat transfer coefficient increases with liquor rate until a critical value and remains reasonably constant above this flow rate, attributed to incomplete/nonuniform wetting of heat transfer surface at lower liquid rates.
2. Overall heat transfer coefficient increases with rotor speed, number of rotor blades and heat flux.
3. Overall heat transfer coefficient increases with a decrease in rotor blade clearance.

4. An increase in viscosity decreases overall heat transfer coefficient.
5. Overall heat transfer coefficient for evaporation is higher than for preheating.

The only correlation available at the present time is the one by Bott and Sheikh [5] for the evaporation of glycerol-water solutions in a laboratory ATFE unit.

$$Nu = 0.65 \quad Re^{0.43} \quad Re'^{0.25} \quad Pr^{0.3} \quad n_B^{0.33} \tag{2.5}$$

where Re film Reynolds number = $\frac{4\tau}{\mu}$

Re' rotational Reynolds number = $\frac{D^2 \ N \ \rho}{\mu}$.

This correlation is of limited applicability to single Newtonian systems only. Even though ATFE units are now in commercial use for over two decades, there is very little published data that would be useful for design purposes.

Consequently it was felt necessary to initiate a series of laboratory investigations on the fundamental aspects of heat transfer and fluid flow behaviour in ATFE units. This study is the first in the proposed series and deals mainly with the heat transfer performance of a laboratory model of ATFE (votator model 04-012, laboratory Turba film processor) using water and glycerol solutions. For the latter system a commercial sample of crude glycerine (76 per cent glycerol) was used with dilution to the desired concentration levels.

One of the limitations on this study has been the total number of variables which could be accommodated with the available imported laboratory model. Variables studied include feed rate, rotor speed and temperature difference driving force; variables like number of blades, blade configuration, blade tip clearance which also have a significant rate in film flow and heat transfer mechanisms could not be included. The results on this investigations are compared with the data reported by Bott and Sheikh [5] and the general observations on performance of ATFE units reported by various investigators.

CHAPTER 3

EXPERIMENTAL

3.1. Apparatus:

An agitated thin film evaporator (Votator Model 04-012 laboratory Turba film processor) was used for the experiments. Important dimensions of this unit are given in Table 3.1. A sketch of the experimental set up is shown in Figure 3.1 and consists of feed tank, Votator and condenser. Feed solution was heated to the desired temperature in a preheater consisting of a steam jacketed stirred vessel. In most of the experiments, feed was preheated to the boiling point and then introduced to the evaporator by a centrifugal pump. Flow rate of feed was measured by means of a rotameter. Feed was distributed uniformly by the centrifugal action of the rotor blades. The concentrated product leaves from the bottom discharge section. Vapors rise through the separator section and pass on to the condenser. Condensate flows to the bottom discharge end of of the condenser. Water was used as cooling medium in the condenser. Temperatures of feed, product and vapor were measured. Saturated steam was used as heating media for evaporator and preheater. Evaporator was operated at atmospheric pressure.

TABLE 3.1

IMPORTANT DIMENSIONS OF AGITATED THIN FILM EVAPORATOR

1. Heat transfer area	: 0.0929 m^2 (1 ft^2)
2. Inside diameter	: 0.0965 m (3.8 in)
3. Shell thickness	: 2.59 mm (0.102 in.)
4. Length of evaporating section	: 0.3048 m (1 ft.)
5. L/D ratio	: 3.2
6. Number of blades	: 4
7. Type of blades	: Fixed
8. Blade tip clearance	: 1 mm (0.03/0.04 in)
9. Rotor speed	: 500-1600 rev/min.

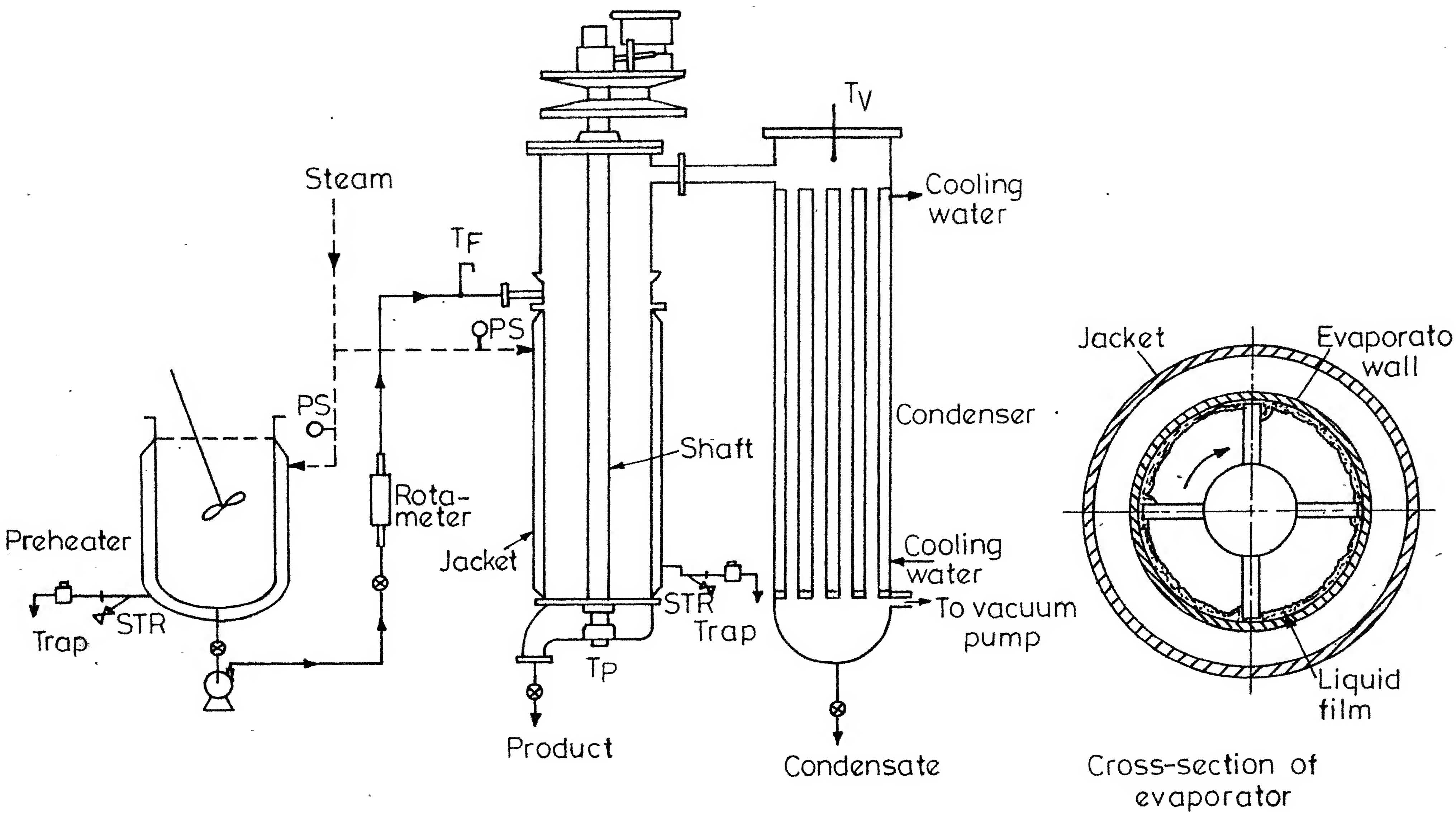

Fig. 3·1 – Sketch of experimental setup.

Rotor drive was accomplished by a direct belt arrangement to provide the variable speed drive for the rotor. Rotor speed was measured by a tachometer/stroboscope.

3.2 Systems Studied:

Water and crude glycerol (spent lye from soap manufacture) were used for the purpose of present study. The concentration of glycerol solution was determined by volumetric analysis using sodium periodate [23]. Viscosity of glycerol solutions was estimated at 100^{o}C, using a capillary viscometer.

3.3 Experimental Method:

Initially about 30 minutes were required to heat the unit uniformly with saturated steam. After that the rotor was started and water was fed to the evaporator. Process liquor was not introduced at this stage. When the unit was operating smoothly on water, process liquor was introduced. Flow rate of feed was adjusted by means of a needle valve in feed line which was usually preheated to its boiling point before entering the evaporator. The readings were recorded under steady state conditions. Flow rates of product and condensate were measured by direct measurement. Temperatures of feed, product and vapor were recorded at steady state. Several readings at different flow rates were recorded

for constant values of steam pressure and rotor speed. Tables of experimental results are given in Appendix.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Calculation of Heat Transfer Coefficient:

Overall heat transfer coefficient and liquid film heat transfer coefficients were calculated from the following equations (4.1) and (4.2) respectively.

$$Q = E\lambda = UA\,\Delta T \qquad (4.1)$$

$$\frac{1}{h_i} = \frac{1}{U} - \frac{x_w}{k_w}\frac{A_i}{A_w} - \frac{1}{h_s}\frac{A_i}{A_o} \qquad (4.2)$$

The steam side heat transfer coefficient was obtained from the Nusselt expression [9] for condensation of vapors on a vertical tube and is given by the equation (4.3).

$$h_s\left[\frac{\mu_f^2}{k_f^3\,\rho_f^2\,g}\right]^{1/3} = 1.47\left[\frac{4\,S}{\mu_f}\right]^{-1/3} \qquad (4.3)$$

$$S = \frac{Q}{\lambda_s\,\pi\,D_o} \qquad (4.4)$$

Mass rate of flow of steam condensate per unit length of perimeter was obtained from above equation (4.4). Steam side heat transfer coefficient was of the order of 10-12 kW/m^2K. The overall heat transfer coefficient and liquid film heat transfer coefficient values for water and glycerol solutions at different flow rates, rotor speed and temperature difference are given in Tables 4.4-4.40 (Appendix). Table 4.1 gives a summary of the operating conditions, for the experiments conducted.

TABLE 4.1

SUMMARY OF OPERATING CONDITIONS

Variable	Water	Glycerine Solution
1. Feed rate, kg/h m^2	100-1300	160 - 1120
2. Feed concentration, wt. per cent	-	40 - 65 percent
3. Evaporation, kg/h m^2	40-170	30 -100
4. Rotor speed, rev/min	600-1600	500-1600
5. Steam pressure, kg/cm^2 (g)	0.7-3.5	1.2-5.6
6. Operating pressure	Atmospheric	Atmospheric
7. Heat flux, kJ/hm^2	$5x10^4$-$40x10^4$	$6x10^4$-$30x10^4$
8. Overall heat transfer coefficient, kW/m^2K	1.5-2.5	0.5-1.4
9. Liquid film heat transfer coefficient, kW/m^2K	2.0-4.5	0.6-1.9

Table 4.2 gives a summary of the relative resistances for water and glycerol solutions. It indicates that the controlling resistance to heat transfer is in the liquid film. The resistance offered by the condensing steam was the lowest. A comparison of these resistances with the values of Ryley [32] summarised in Table 2.2, shows that the metal wall contributes less resistance to heat transfer due to small thickness of metal wall in the laboratory ATFE unit as compared to the wall thickness in commercial units.

4.2 Effect of Feed Rate on Heat Transfer Coefficient:

It is of interest to know how the feed rate affects the heat transfer coefficient. Tables 4.4 to 4.40 give an account of the influence of feed rate on liquid film heat transfer coefficient at different constant values of rotor speed and overall temperature difference for water and glycerol solutions. Figure 4.1 shows the influence of feed rate on heat transfer coefficient at various values of overall temperature difference with water as test liquid, (rotor speed =600 rev/min). The results show that as feed rate is increased from 110 to 600 kg/h m^2, the heat transfer coefficient increases sharply. The heat transfer coefficient remains constant after a feed rate of 800 kg/h m^2. The initial steep portion of the curve indicates that at low feed rates the heating surface is only partially wetted. Heat transfer coefficient increases as more and more of the surface is wetted by an increase

TABLE 4.2

RELATIVE HEAT TRANSFER RESISTANCE IN ATFE

Resistance	65 per cent glycerol solution	40 per cent glycerol solution	Water
R_i	75.4	66.5	49.4
R_w	15.1	20.6	31.0
R_o	9.5	12.9	19.6
R	100	100	100

R_i = Resistance of process liquid film

R_w = Resistance of metal wall

R_o = Resistance of condensing steam film

$h_s = 8.75\ kW/m^2K$

$h_i = 1.1\ kW/m^2K$ for 65 per cent glycerol solution

$h_i = 1.7\ kW/m^2K$ for 40 per cent glycerol solution

$h_i = 3.5\ kW/m^2K$ for water

$x = 0.00259\ m$

$k_w = 11.9$ Kcal/h m C

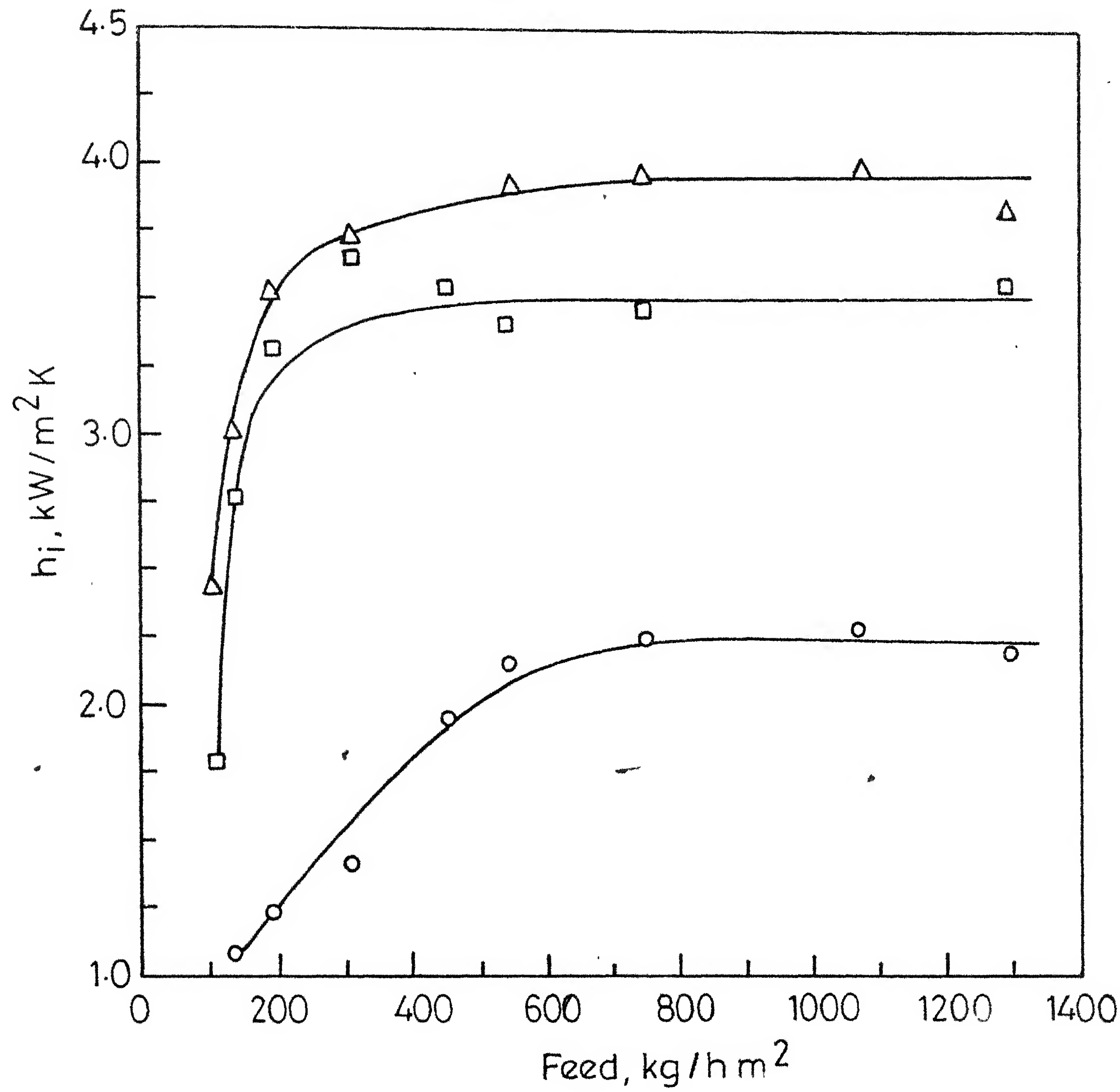

Fig. 4.1 - Effect of feed rate on liquid film heat transfer coefficient for water. (N=600 rev/min)

	ΔT, °C
△	42.5
□	39.1
○	16.3

in feed rate. Any further increase in feed rate does not affect the heat transfer coefficient, once the whole surface has become wetted. The comparative results for water are given by Reay [30]. He studied the effect of feed rate on heat transfer coefficient for various values of blade tip clearance. He also observed similar variation of heat transfer coefficient with feed rate as discussed above.

Figure 4.2 shows the influence of feed rate on heat transfer coefficient for water at rotor speed of 1250 rev/min and the results are similar to Figure 4.1. Figures 4.3 - 4.4 show the effect of feed rate on heat transfer coefficient at various values of rotor speeds with 40 and 65 per cent glycerol solutions respectively. The results show that heat transfer coefficient increases with feed rate upto a critical value and then remains constant. Figure 4.5 gives comparative results for water and glycerol solutions at rotor speeds of 600 and 1250 rev/min. The heat transfer coefficient for water is higher than for glycerol solutions. As the feed rate is reduced, a critical point is reached where the thin film becomes unstable and tends to break up into rivulets, leaving hot spots on the wall. The critical feed rate for water and glycerol solutions was in the range of 50-80 kg/h as compared to 45-70 kg/h as reported by Reay [30].

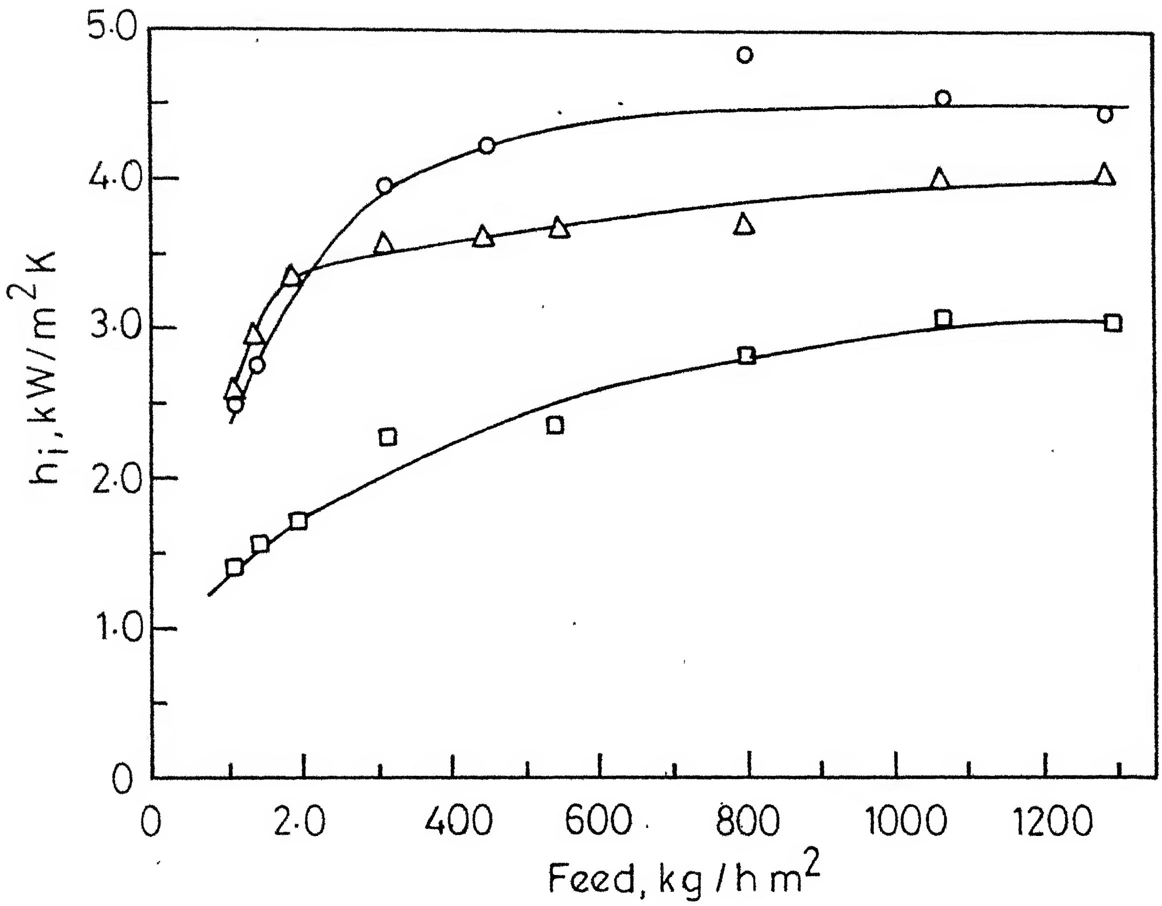

Fig. 4.2 - Effect of feed rate on liquid film heat transfer coefficient for water. (N = 1250 rev/min)

ΔT, °C

○ 39.1

△ 27.0

□ 9.0

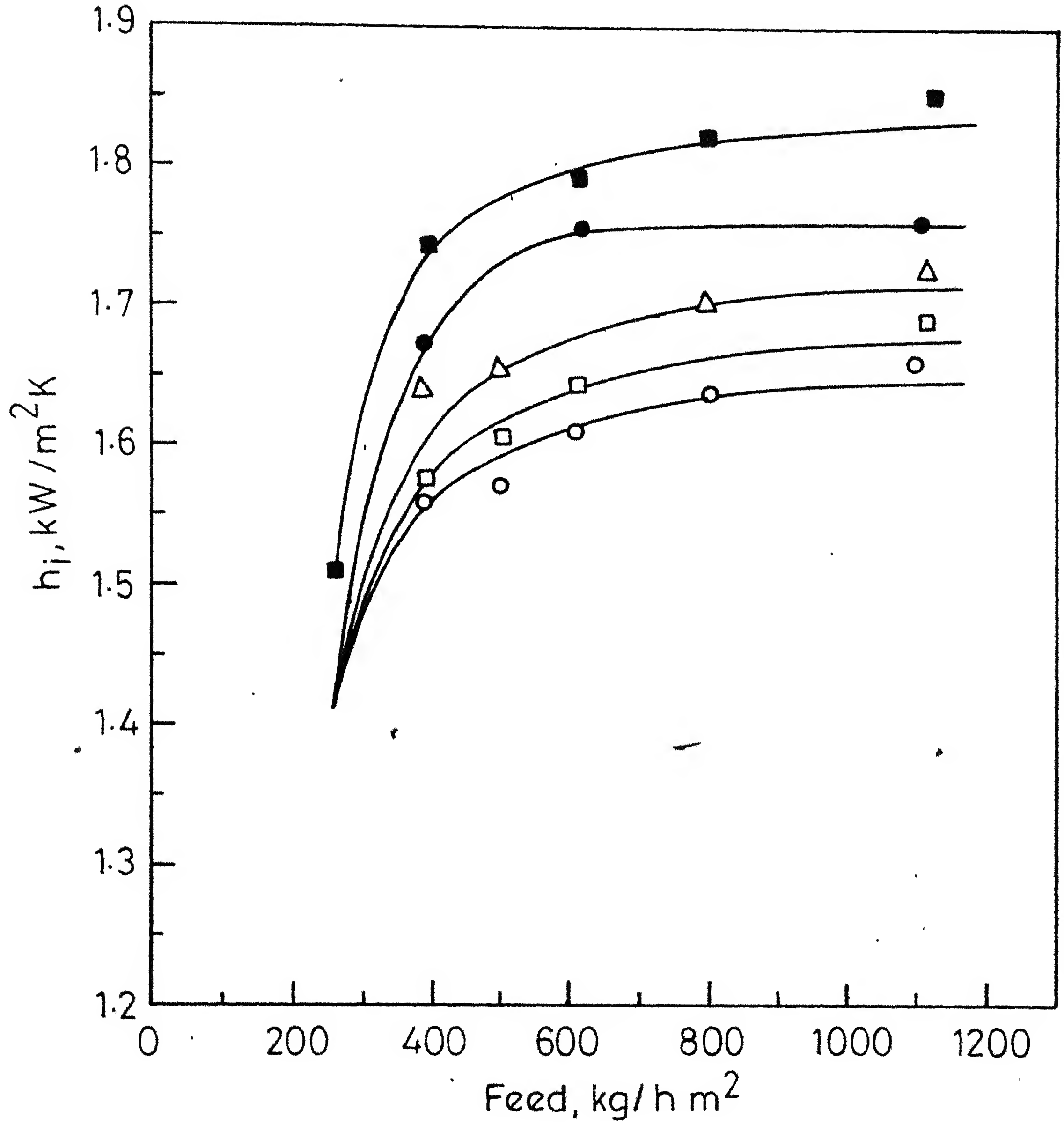

Fig. 4·3 - Effect of feed rate on liquid film heat transfer coefficient for 40% glycerol solution.
(ΔT= 51°C)

	N, rev/min
○	600
□	900
■	1250
●	1400
△	1600

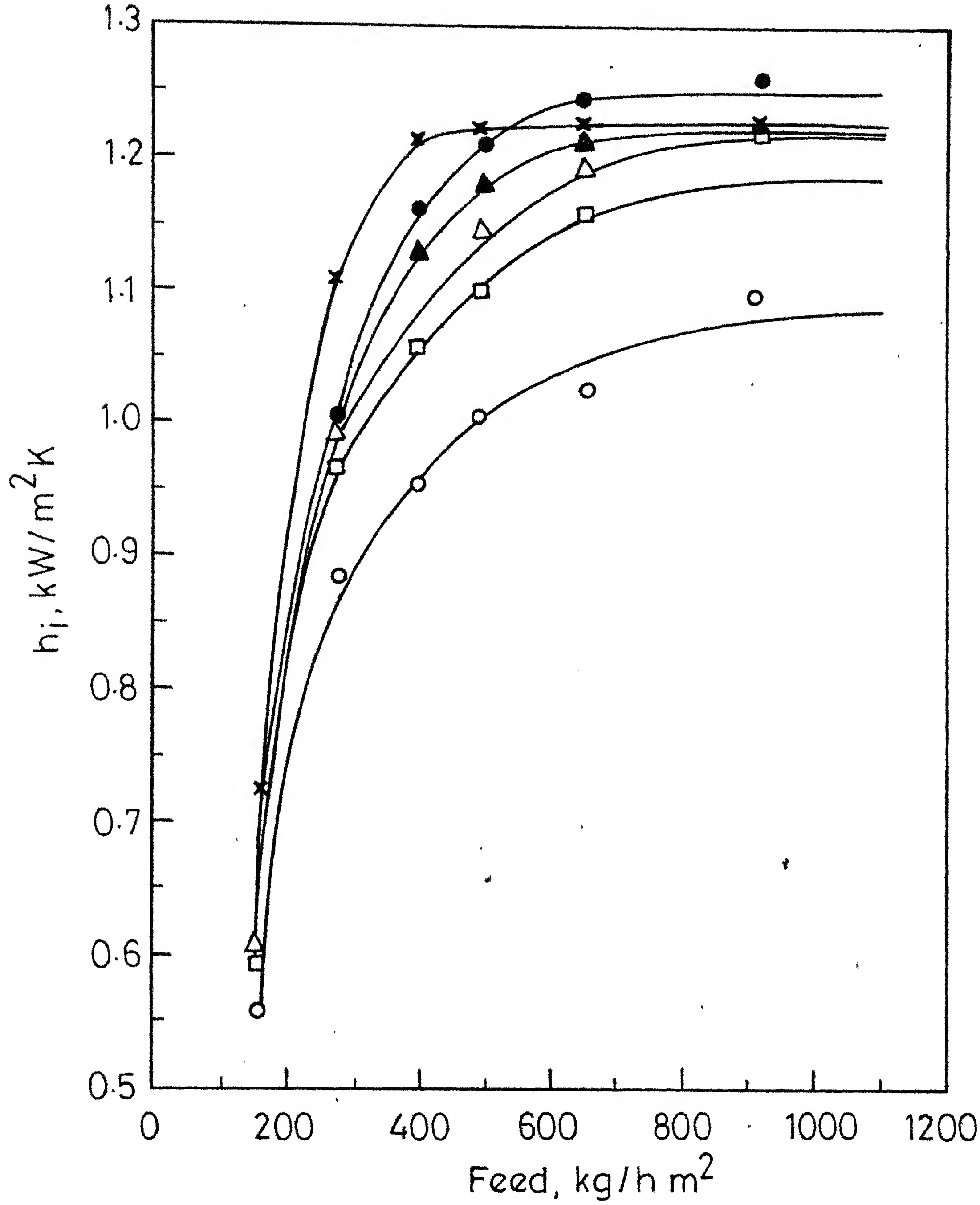

Fig. 4.4 – Effect of feed rate on liquid film heat transfer coefficient for 65% glycerol solution. ($\Delta T = 50°C$)

	N, rev/min
▲	1600
●	1400
×	1250
△	900
□	600
○	500

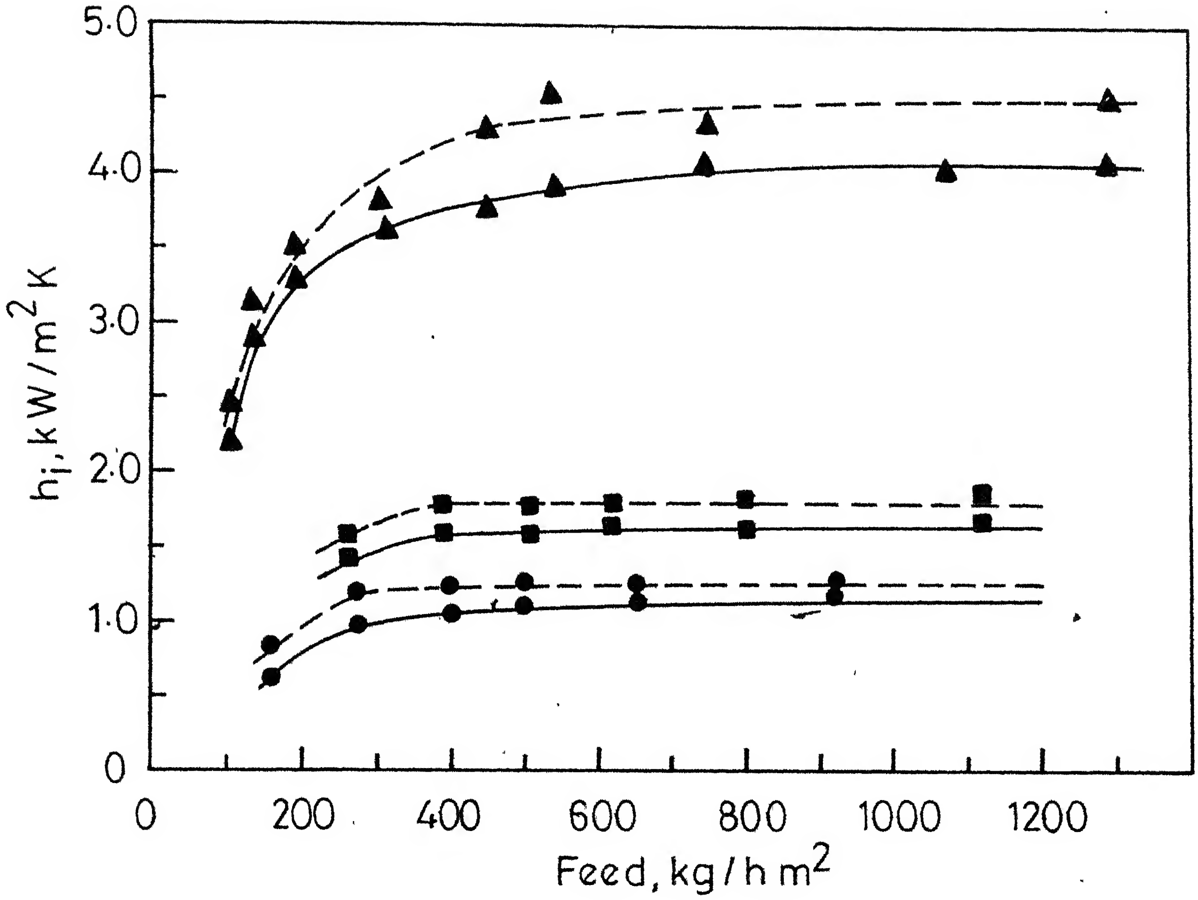

Fig. 4.5 - Effect of feed rate on liquid film heat transfer coefficient for aqueous solution ($\Delta T = 50°C$)

—— 600 rev/min ---- 1250 rev/min

▲ Water

■ 40% glycerol

● 65% glycerol

4.3 Effect of Heat Flux on Heat Transfer Coefficient:

Figure 4.6 based on data of Tables 4.19 and 4.20 shows the influence of heat flux on heat transfer coefficient for water and glycerol solutions. Heat transfer coefficient increased from 2.4 to 4.25 kW/m^2K with an increase in heat flux from 5×10^4 to 35×10^4 $kJ/h\ m^2$. The initial portion of the curve is steep and after a critical heat flux. There is small increase in heat transfer coefficient because there is no further decrease in resistance offered by thin liquid film. The results obtained are in good agreement with Reay [30] who also has described the effect of heat flux on heat transfer coefficient.

4.3.1 Effect of Temperature Difference on Heat Transfer Coefficient:

Figure 4.7 shows the effect of overall temperature difference on heat transfer coefficient at rotor speed of 600 rev/min with water. Heat transfer coefficient increased from 2 to 4 kW/m^2K by increasing temperature difference from 16 to 48^oC. Gudheim and Donovan [15] have described the influence of temperature difference on heat transfer coefficient in ATFE and the results were similar to Figure 4.7. Effect of operation under vacuum which can raise the available temperature difference was not studied in this work due to operational limitations.

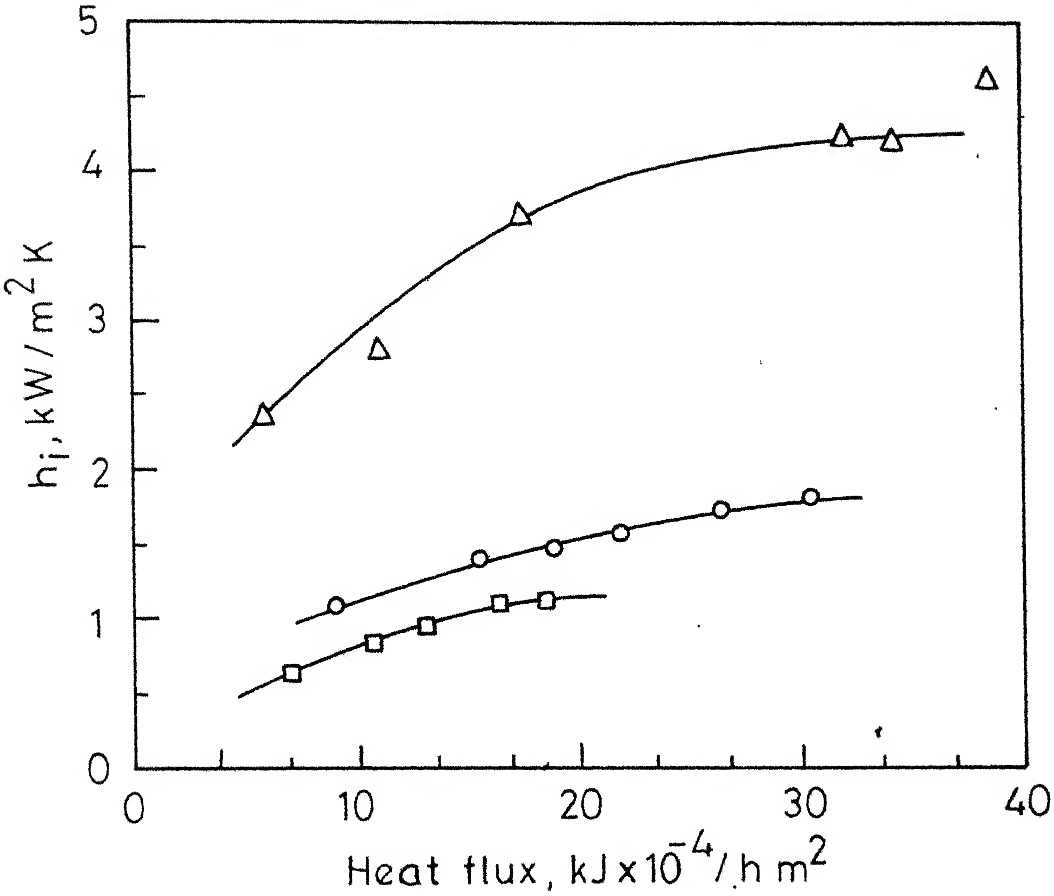

Fig. 4·6 – Effect of heat flux on liquid film heat transfer coefficient for aqueous solutions.
(Feed = 506 kg / h m^2, N = 1250 rev / min)

Δ Water
o 40 % glycerol
□ 65 % glycerol

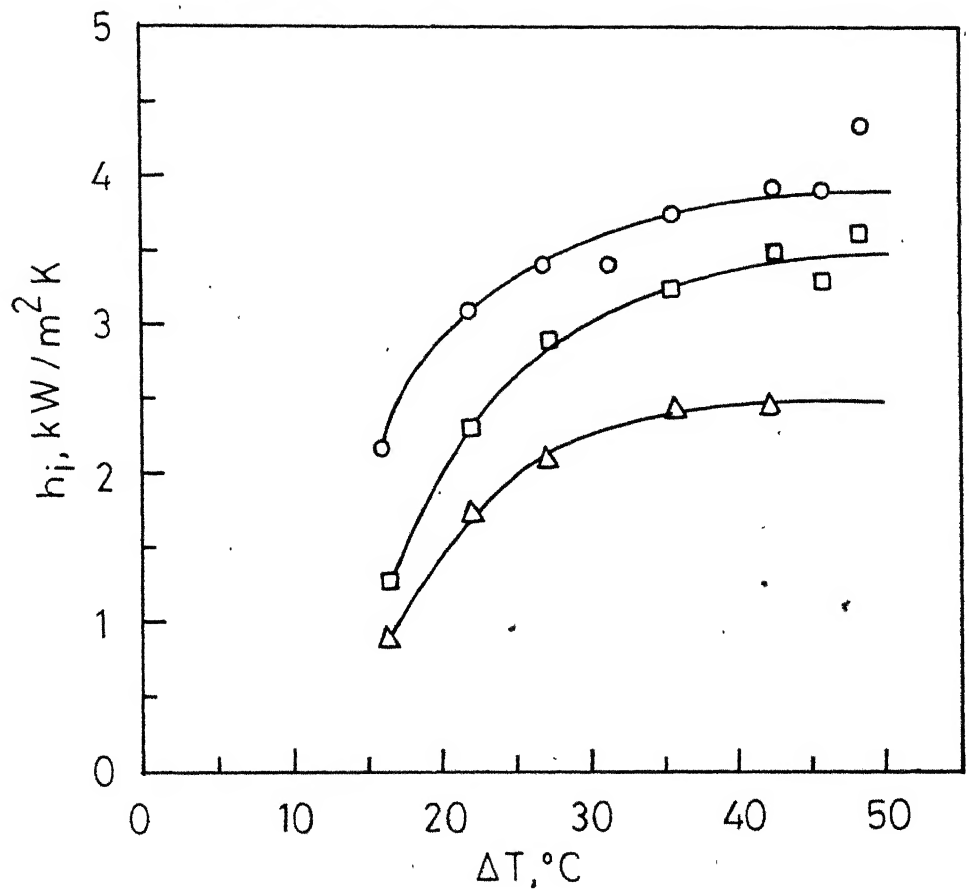

Fig.4·7 - Effect of overall temperature difference on liquid film heat transfer coefficient for water.
(N = 600 rev / min)

Feed	kg / h m^2
o	543
□	194
Δ	111

4.4 Effect of Rotor Speed on Heat Transfer Coefficient:

The results of Tables 4.4 to 4.40 are summarised in Figure 4.8 to 4.10 to show the influence of rotor speed on heat transfer coefficient for water and glycerol solutions. Figure 4.8 shows the effect of rotor speed (600-1600 rev/min) on liquid film heat transfer coefficient at different values of feed rates (262 to 800 kg/h m^2) with 40 per cent glycerol solution. There was no effect of rotor speed at low flow rates but became significant at higher feed flow rates. Heat transfer coefficient increased slightly from 1.7 to 1.85 kW/m^2K with an increase in rotor speed from 600 to 1600 rev/min. Heat transfer coefficient shows a slight maximum at rotor speed of 1200-1300 rev/min. Reay has also reported the small effect of rotor speed (600 to 3000 rev/min) on heat transfer coefficient. A similar behaviour was observed for 65 per cent glycerol solution as shown by Figure 4.9.

Figure 4.10 shows the effect of rotor speed on heat transfer coefficient for water and glycerol solutions, at a feed rate of 506 kg/h m^2. The results show that rotor speed has a small effect on heat transfer coefficient which is in good agreement with Reay [30] and Dieter [10].

4.5 Dimensional Analysis:

The liquid film heat transfer coefficient is dependent on several variables as given by equation (4.5).

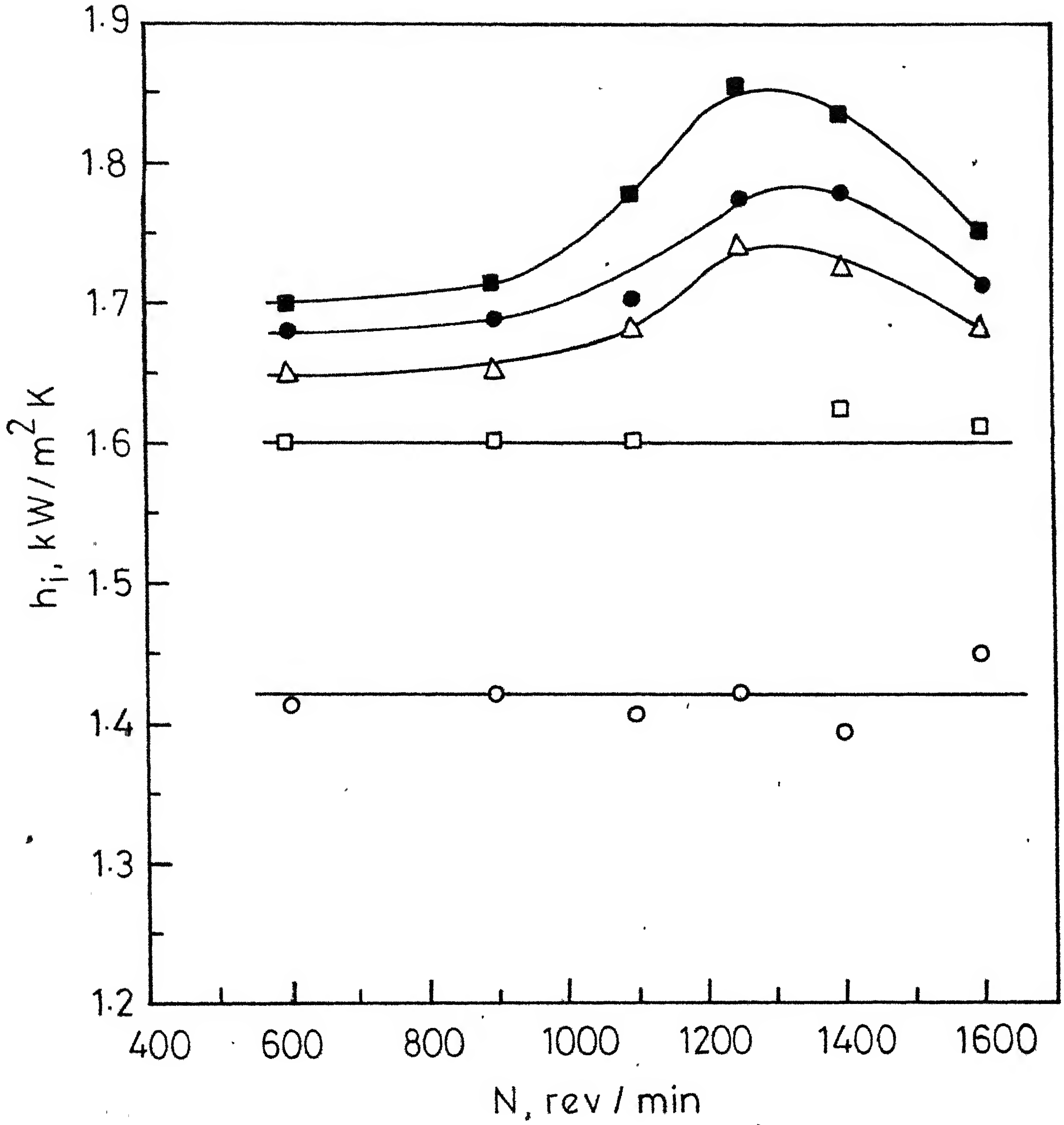

Fig. 4.8-Effect of rotor speed on liquid film heat transfer coefficient for 40% glycerol solution.

($\Delta T = 51°C$) Feed, $kg/h\ m^2$

○	262
□	380
△	506
●	616
■	800

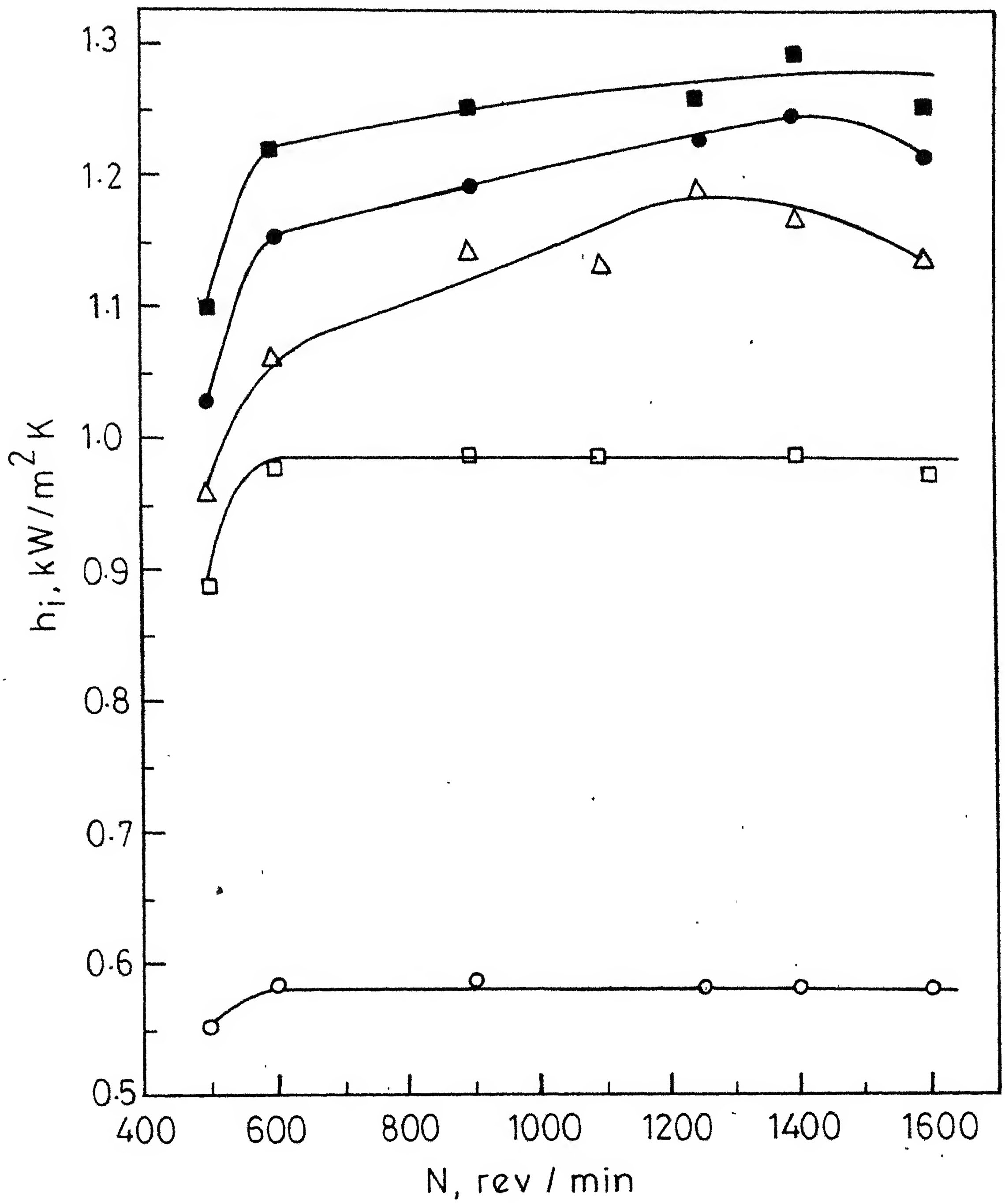

Fig. 4.9 - Effect of rotor speed on liquid film heat transfer coefficient for 65% glycerol solution. ($\Delta T = 50\,^{\circ}C$)

Feed, kg / h m^2

○	160
□	276
△	398
●	659
■	919

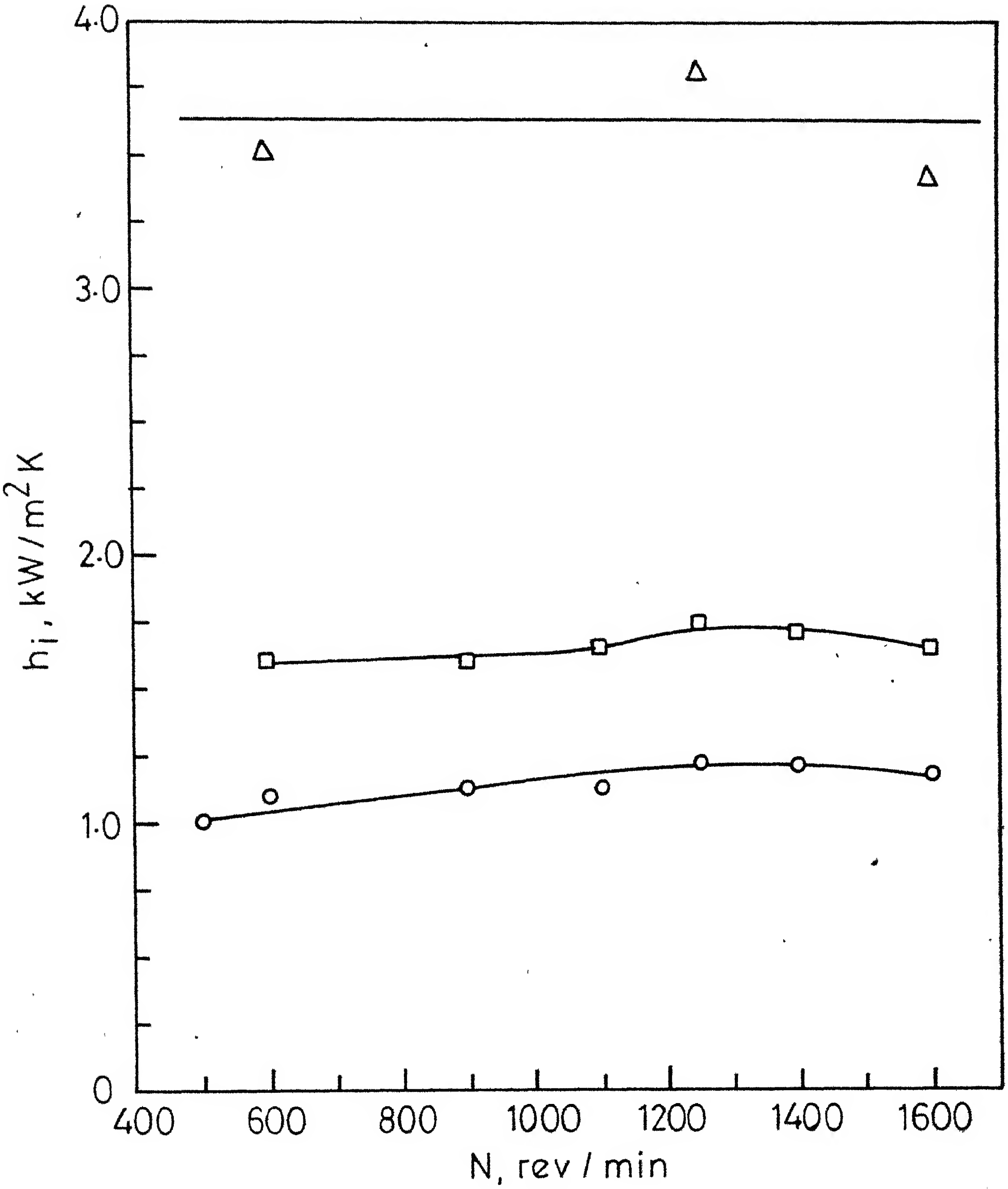

Fig. 4.10- Effect of rotor speed on liquid film heat transfer coefficient for aqueous solutions. ($\Delta T = 51\,°C$, Feed = 506 kg / h m^2).

△ Water

□ 40% glycerol

○ 65% glycerol

$$h_i = f(D,\ N, n_B, \rho,\ \mu,\ u,\ k,\ \delta,\ C_p) \tag{4.5}$$

Dimensional analysis of the above expression leads to equations (4.6) to (4.8).

$$\frac{h_i D}{k} = f\left(\frac{D\ u\ \rho}{\mu},\ \frac{D^2 N \rho}{\mu},\ \frac{C_p \mu}{k},\ n, \delta\right) \tag{4.6}$$

$$Nu = f(Re,\ Re',\ Pr,\ n_B, \delta) \tag{4.7}$$

$$Nu = C\ Re^a\ Re'^b\ Pr^c \tag{4.8}$$

The number of blades and blade tip clearance were constant for all experiments of this study and hence they are included in the constant, C. The characteristic length in the dimensionless groups of equation (4.6) is the inside diameter of the evaporator. This criterion is not reliable for thin film systems when diameter is substantially different from the one used in the experiments. Due to this, the equivalent diameter was used as the characteristic length as given by equation 4.9 by Bott and Romero [6].

$$D_e = 4\ r_h = 2\sqrt{2}\left[\frac{\bar{F}\ \mu}{k_1 \rho^2\ g\ n_B}\right]^{1/4} \tag{4.9}$$

where $k_1 = 0.0703$

Dimensionless groups used for the correlation were modified according to the above definition and given by equations (4.10) to (4.13).

$$Re = \frac{4\ \tau}{\mu} \qquad (4.10)$$

$$Re' = \frac{D\ D_e\ N \rho}{\mu} \qquad (4.11)$$

$$Pr = \frac{C_p\ \mu}{k} \qquad (4.12)$$

$$Nu = \frac{h_i\ D_e}{k} \qquad (4.13)$$

The correlation can be written as given in equation (4.14) so that the logarithms of the dimensionless groups are linearly dependent.

$$Nu = C\ Re^a\ Re'^b\ Pr^c \qquad (4.14)$$

$$\log Nu = \log C + a \log Re + b \log Re' + c \log Pr$$

Experimental data of Tables 4.4 to 4.40 were used to fit equation (4.14) by the method of least squares [21].

The final correlation is given by equation (4.15).

$$Nu = 0.29\ Re^{0.39}\ Re'^{0.13}\ Pr^{0.25} \qquad (4.15)$$

Some values of the dimensionless groups and regression values of Nusselt number at different flow rates and rotor speeds are given in Table 4.3. By plotting Nusselt number against flow Reynolds number at constant rotary Reynolds number and Prandtl number, a straight line of slope 0.39 was obtained. By plotting Nusselt number against rotary Reynolds number, a straight line with slope 0.13 was obtained. Similarly a straight line with slope 0.25 was obtained for Nusselt number against Prandtl number. Figure 4.11 shows the plot of experimental values of Nusselt number against regression values

TABLE 4.3

EXPERIMENTAL VALUES OF DIMENSIONLESS GROUPS

F, kg/h m^2	N, rev/min	D_e, m	Re	Re'	Pr	Nu	Nu_{Cal}
262	600	0.00311	77	22680	7.21	9.83	8.75
506	600	0.00354	202	32400	5.45	12.01	11.84
799	600	0.00389	373	39960	4.78	13.07	14.12
389	1250	0.00335	140	59400	6.09	12.81	11.90
616	1250	0.00367	267	74880	5.05	13.49	14.1
1122	1250	0.00422	552	93960	4.53	16.43	16.34
276	900	0.00374	47	22320	15.19	10.35	9.45
493	900	0.00428	92	27000	13.76	13.25	12.57
919	900	0.00497	187	33120	12.87	16.63	16.27
160	1600	0.00327	27	34200	15.45	5.34	6.95
398	1600	0.00407	72	45000	14.28	12.70	11.44
659	1600	0.00459	129	53280	13.32	15.03	14.75
140	1250	0.00190	80	79560	1.79	10.29	8.95
510	1250	0.00259	278	108360	1.79	14.69	13.40
543	1250	0.00307	547	128520	1.79	18.88	17.81
1072	1250	0.00370	1164	155160	1.79	25.22	25.40

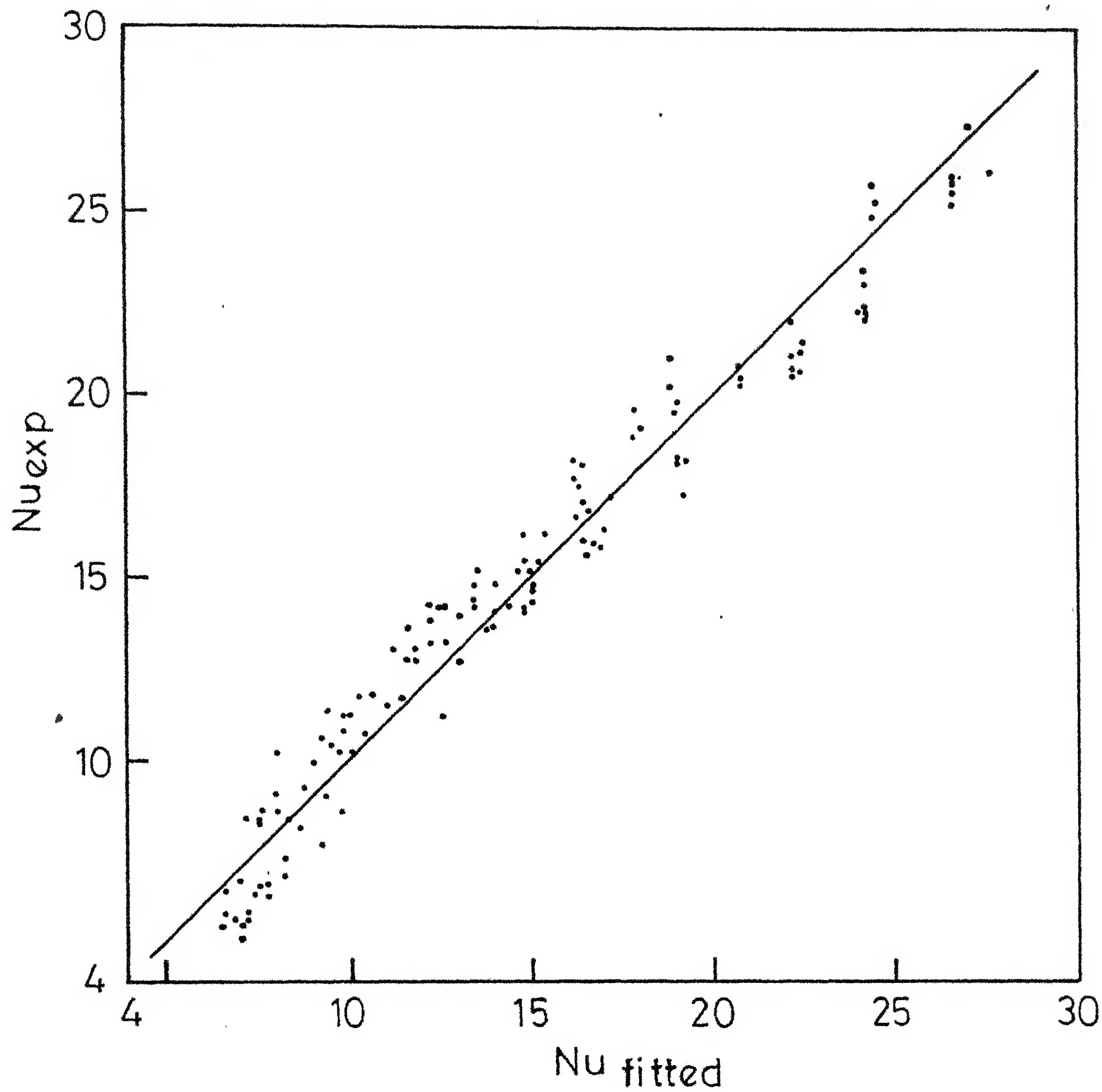

Fig. 4.11 - Plot of $Nu_{exp.}$ vs. Nu_{fitted}.

$Nu = 0.29\ Re^{0.39}\ Re^{0.13}\ Pr^{0.25}$.

of Nusselt number. Heat transfer coefficient can be estimated with an accuracy of ± per cent by equation (4.15) for the range of dimensionless groups (Re = 50-1500, Re' = 1.0×10^4 - 17×10^4 and Pr = 1.8 - 15.5). Bott and Sheikh [5] also have given a very similar correlation for the estimation of heat transfer coefficient to boiling glycerol solution as given by equation (4.16).

$$Nu = 0.65 \quad Re^{0.25} \; Re'^{0.43} \; Pr^{0.3} \; n_B^{0.33} \qquad (4.16)$$

A comparison of the exponents obtained in present work with that of Bott and Sheikh [5] shows a large difference in the value of exponent b. This is probably caused by the use of equivalent diameter for the rotary Reynolds number in this work, whereas Bott and Sheikh [5] have used the tube diameter as the characteristic dimension. The difference in the values of constant C is due to the inclusion of the number of blades in the correlation used for this work.

Exponent	This Study	Bott and Sheikh [5]
a	0.39	0.25
b	0.13	0.43
c	0.25	0.30
C	0.29	0.65

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

5.1 Summary:

This study describes the heat transfer in an agitated thin film evaporator (Votator Model 04-012, Laboratory Turba Film Processor). Commercial sample of crude glycerine (76 per cent Glycerol) was used in this work with dilutions to the desired concentration levels. The following conclusions are based on the results of present work.

1. Heat transfer coefficient increases with feed rate upto a critical value and remains constant above this feed rate. The critical feed rate for water and glycerol solutions is in the range of 600-800 kg/h m^2.
2. An increase in heat flux increases heat transfer coefficient.
3. An increase in overall temperature difference also increases heat transfer coefficient.
4. Rotor speed has a small influence on heat transfer coefficient.
5. Experimental data are correlated by the following dimensionless groups.

$$Nu = 0.29 \quad Re^{0.39} \quad Re'^{0.13} \quad Pr^{0.25} \qquad (5.1)$$

RECOMMENDATIONS

. Following modifications are recommended in this work:

1. In this investigation the rotor configuration was constant and so the effect of type agitator (fixed or hinged), number of blades and blade tip clearance on heat transfer coefficient could not be studied. There is very limited data in literature on the influence of these variables on rate of heat transfer, and there is no correlation to accommodate these variables. So the study of the number of blades and blade tip clearance is recommended.

2. The influence of feed rate, rotor speed, heat flux on heat transfer coefficient was studied in this work for Newtonian liquids only, which have low viscosity at boiling point. The influence of viscosity for Non-Newtonian systems, whose viscosity change with the rate of shear operating in ATFE is recommended.

3. Effect of vacuum which can raise overall temperature difference was not studied in this investigation due to operational limitations which can be overcome in future work.

4. During experimental work, there were fluctuations in feed rate which had to be controlled manually. So the controlling device for feed flow rate should be used in future work.

5. A temperature controller should be installed for preheater so that the temperature of feed can be raised to any desired temperature with accuracy.

6. Experimental studies on agitated thin film processor for various processes like Dehydration of organics, deodorization, distillation of organics, chemical reactions etc. is suggested for future work.

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APPENDIX

NOMENCLATURE

DE Equivalent diameter, m

E Evaporation, kg/h m^2

F Feed rate, kg/h m^2

HI Liquid film heat transfer coefficient, W/m^2 K

N Rotor speed, rev/min

P Product rate, kg/h m^2

Q Heat flux, kJ/h m^2

U Overall heat transfer coefficient, W/m^2K

Dimensionless Numbers

NU Nusselt number, HIxDE/k

NU2 Nusselt number HIxD/k based on tube diameter

PR Prandtl number = Cp μ/k

RE Flow Reynolds number = $4\tau/\mu$

RE1 Rotary Reynolds number = DxDExN'x ρ/μ

RE2 Rotary Reynolds number based on tube diameter $=D^2N'\rho$,

RE3 Rotary Reynolds number = DE^2xN'x ρ/μ

APPENDIX

NOMENCLATURE

DE Equivalent diameter, m

E Evaporation, kg/h m^2

F Feed rate, kg/h m^2

HI Liquid film heat transfer coefficient, W/m^2 K

N Rotor speed, rev/min

P Product rate, kg/h m^2

Q Heat flux, kJ/h m^2

U Overall heat transfer coefficient, W/m^2K

Dimensionless Numbers

NU Nusselt number, HIxDE/k

NU2 Nusselt number HIxD/k based on tube diameter

PR Prandtl number = Cp μ/k

RE Flow Reynolds number = $4\tau/\mu$

RE1 Rotary Reynolds number = D*DExN'x ρ/μ

RE2 Rotary Reynolds number based on tube diameter =D^2N'ρ.

RE3 Rotary Reynolds number = DE^2xN'x ρ/μ

TABLE 4. 4

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 1250.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	41.5	34.4	123.	135.0	82.8	96105.	643.	722.
2	276.	43.7	51.0	223.	132.0	79.8	145522.	925.	1111.
3	398.	47.6	58.1	337.	126.0	76.1	170372.	991.	1213.
4	493.	50.3	60.3	433.	122.0	74.1	180191.	995.	1221.
5	659.	52.8	60.3	596.	118.0	71.5	189085.	996.	1224.
6	919.	54.5	56.4	874.	115.0	69.2	194931.	993.	1221.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00325	26.	785733.	15.45	195.88	26497.	6.61	894.
2	.00373	46.	794320.	15.19	299.31	30710.	11.57	1187.
3	.00406	72.	835405.	14.28	323.25	35158.	13.60	1480.
4	.00428	92.	850062.	13.76	318.97	37691.	14.14	1671.
5	.00459	129.	875666.	13.32	318.83	41604.	15.15	1977.
6	.00497	187.	897287.	12.87	314.93	46234.	16.23	2382.

TABLE 4. 5

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 1400.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	43.0	28.4	128.	133.0	79.0	82340.	532.	584.
2	276.	46.4	49.5	224.	128.0	79.2	139505.	835.	981.
3	398.	48.4	57.0	336.	125.0	75.9	166986.	958.	1163.
4	493.	50.3	59.8	434.	122.0	74.0	179248.	990.	1213.
5	659.	52.2	59.6	597.	119.0	71.5	189494.	1009.	1245.
6	919.	54.0	58.1	872.	116.0	69.4	201370.	1037.	1290.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	880020.	15.45	158.44	29832.	5.37	1011.
2	.00373	47.	889638.	15.19	264.45	34422.	10.23	1332.
3	.00406	72.	935654.	14.28	310.08	39391.	13.05	1658.
4	.00428	92.	952069.	13.76	316.87	42218.	14.05	1872.
5	.00459	129.	980746.	13.32	324.27	46602.	15.41	2214.
6	.00497	186.	1004962.	12.87	332.67	51769.	17.14	2667.

TABLE 4. 6

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 1100.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	40.0	30.1	125.	137.0	80.0	87645.	609.	678.
2	276.	45.8	48.4	225.	129.0	78.9	137862.	837.	984.
3	398.	47.8	53.8	337.	126.0	75.2	160997.	937.	1130.
4	493.	50.3	56.0	435.	122.0	73.3	170763.	943.	1142.
5	659.	52.8	56.0	598.	118.0	71.0	179605.	946.	1147.
6	919.	54.5	54.9	871.	115.0	69.1	191599.	976.	1195.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	691445.	15.45	183.92	23405.	6.23	792.
2	.00374	47.	699001.	15.19	265.23	27060.	10.27	1048.
3	.00407	72.	735157.	14.28	301.22	30984.	12.70	1306.
4	.00428	92.	748054.	13.76	298.22	33206.	13.24	1474.
5	.00459	129.	770586.	13.32	298.90	36643.	14.21	1742.
6	.00497	187.	789613.	12.87	308.16	40694.	15.88	2097.

TABLE 4. 7

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 600.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	43.7	29.7	132.	132.0	79.8	84725.	539.	592.
2	276.	45.1	46.3	231.	130.0	78.1	133895.	825.	967.
3	398.	49.1	52.7	346.	124.0	74.9	156542.	887.	1058.
4	493.	50.9	55.1	440.	121.0	73.2	167540.	914.	1099.
5	659.	52.2	54.9	606.	119.0	70.9	179080.	954.	1159.
6	919.	54.0	54.3	873.	116.0	69.1	192814.	993.	1221.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	377152.	15.45	160.62	12771.	5.44	432.
2	.00374	47.	381274.	15.19	260.67	14776.	10.10	573.
3	.00407	73.	400995.	14.28	281.84	16906.	11.88	713.
4	.00429	92.	408030.	13.76	286.98	18117.	12.74	804.
5	.00459	129.	420320.	13.32	302.01	19991.	14.36	951.
6	.00497	187.	430698.	12.87	314.79	22199.	16.22	1144.

TABLE 4. 8

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 500.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	45.1	29.1	132.	130.0	79.4	82528.	509.	556.
2	276.	46.4	44.1	230.	128.0	77.4	127819.	765.	884.
3	398.	50.3	49.5	350.	122.0	74.2	147360.	814.	954.
4	493.	52.2	52.7	436.	119.0	72.8	159657.	850.	1007.
5	659.	54.0	52.1	600.	116.0	70.6	167365.	862.	1024.
6	919.	55.1	51.2	872.	114.0	68.8	180855.	911.	1098.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	314293.	15.45	150.73	10648.	5.11	361.
2	.00374	47.	317728.	15.19	238.31	12326.	9.25	478.
3	.00407	76.	334162.	14.28	254.22	14104.	10.73	595.
4	.00429	96.	340025.	13.76	263.01	15107.	11.69	671.
5	.00459	129.	350266.	13.32	266.78	16669.	12.70	793.
6	.00498	187.	358915.	12.87	283.08	18507.	14.60	954.

TABLE 4. 9

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 900.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	43.7	30.5	131.	132.0	80.2	86352.	549.	605.
2	276.	45.1	47.6	229.	130.0	78.6	136692.	842.	992.
3	398.	47.8	55.3	342.	126.0	75.5	164279.	956.	1159.
4	493.	50.6	56.8	438.	121.5	73.5	171982.	944.	1143.
5	659.	52.2	56.6	603.	119.0	71.1	182867.	974.	1190.
6	919.	54.0	56.0	866.	116.0	69.2	196617.	1012.	1251.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	565728.	15.45	164.06	19144.	5.55	648.
2	.00374	47.	571910.	15.19	267.21	22150.	10.35	858.
3	.00407	72.	601492.	14.28	308.86	25338.	13.01	1067.
4	.00428	92.	612044.	13.76	298.62	27162.	13.25	1205.
5	.00459	129.	630479.	13.32	310.02	29977.	14.74	1425.
6	.00497	187.	646047.	12.87	322.68	33290.	16.63	1715.

TABLE 4.10

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 65 PERCENT GLYCEROL AT N= 1600.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 5.0

	F	DT	E	P	TP	X	Q	U	HI
1	160.	43.7	29.1	131.	132.0	79.4	83331.	530.	581.
2	276.	46.4	48.4	225.	128.0	78.9	137168.	821.	962.
3	398.	47.8	53.8	337.	126.0	75.2	160997.	937.	1130.
4	493.	50.3	58.1	433.	122.0	73.7	175477.	969.	1181.
5	659.	52.2	57.9	600.	119.0	71.3	185707.	989.	1213.
6	919.	54.0	56.0	872.	116.0	69.2	196617.	1012.	1251.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00327	27.	1005738.	15.45	157.69	34074.	5.34	1154.
2	.00374	47.	1016730.	15.19	259.15	39360.	10.03	1524.
3	.00407	72.	1069319.	14.28	301.22	45068.	12.70	1899.
4	.00428	92.	1088079.	13.76	308.52	48272.	13.69	2142.
5	.00459	129.	1120852.	13.32	316.10	53278.	15.03	2532.
6	.00497	187.	1148528.	12.87	322.68	59183.	16.63	3050.

TABLE 4.11

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 600.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 3.9

	F	DT	E	P	TP	X	Q	U	HI
1	262.	51.6	86.1	174.	107.0	59.6	207197.	1115.	1414.
2	389.	52.7	93.6	298.	105.0	52.7	229279.	1208.	1575.
3	506.	53.3	94.1	405.	104.0	49.1	234758.	1224.	1604.
4	616.	53.3	93.6	517.	104.0	47.2	238940.	1246.	1643.
5	799.	54.1	91.5	689.	102.5	45.2	239137.	1228.	1612.
6	1122.	54.4	90.4	1033.	102.0	43.5	248508.	1270.	1689.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00311	77.	704809.	7.21	304.72	22740.	9.83	734.
2	.00335	140.	819447.	6.09	333.04	28473.	11.57	989.
3	.00354	202.	863300.	5.45	327.24	32424.	12.01	1190.
4	.00368	268.	944640.	5.05	332.28	35981.	12.66	1370.
5	.00389	373.	992906.	4.78	323.94	40063.	13.07	1616.
6	.00422	553.	1030516.	4.53	334.16	45045.	14.61	1969.

TABLE 4.12

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 900.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 97.5

STEAM PRESSURE= 6.9

	F	DT	E	P	TP	X	Q	U	HI
1	262.	50.5	86.1	173.	109.0	59.6	208372.	1146.	1466.
2	389.	52.7	93.0	297.	105.0	52.6	227833.	1200.	1561.
3	506.	53.8	94.1	409.	103.0	49.1	233379.	1204.	1570.
4	616.	54.1	94.7	515.	102.5	47.3	238737.	1226.	1609.
5	799.	54.4	93.6	711.	102.0	45.3	242797.	1240.	1635.
6	1122.	54.4	91.5	1025.	102.0	43.6	250930.	1282.	1712.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00311	77.	1057214.	7.21	315.76	34110.	10.19	1101.
2	.00335	140.	1229170.	6.09	330.20	42720.	11.48	1485.
3	.00354	202.	1324950.	5.45	320.35	48636.	11.76	1785.
4	.00368	268.	1416960.	5.05	325.33	53958.	12.39	2055.
5	.00389	372.	1489359.	4.78	328.57	60072.	13.25	2423.
6	.00422	553.	1545775.	4.53	338.68	67560.	14.80	2953.

TABLE 4.13

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 1100.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 3.9

	F	DT	E	P	TP	X	Q	U	HI
1	262.	51.1	85.0	172.	108.0	59.3	205384.	1117.	1418.
2	389.	52.7	93.0	297.	105.0	52.6	227833.	1200.	1561.
3	506.	53.0	94.7	405.	104.5	49.2	236896.	1241.	1635.
4	616.	53.6	94.3	513.	103.5	47.2	239516.	1242.	1637.
5	799.	54.4	96.4	710.	102.0	45.5	249094.	1273.	1694.
6	1122.	54.4	94.7	1021.	102.0	43.7	258195.	1319.	1781.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00312	77.	1292150.	7.21	305.45	41715.	9.86	1347.
2	.00335	140.	1502319.	6.09	330.20	52213.	11.48	1815.
3	.00354	202.	1619383.	5.45	333.56	59434.	12.24	2181.
4	.00368	268.	1731840.	5.05	331.14	65955.	12.61	2512.
5	.00389	372.	1820328.	4.78	340.36	73387.	13.72	2959.
6	.00422	552.	1889280.	4.53	352.46	82542.	15.40	3606.

TABLE 4.14

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 1250.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 3.9

	F	DT	E	P	TP	X	Q	U	HI
1	262.	49.6	86.1	172.	110.5	59.6	209254.	1171.	1507.
2	389.	49.9	93.6	296.	110.0	52.7	234218.	1303.	1743.
3	506.	52.2	96.9	404.	106.0	49.5	243776.	1298.	1737.
4	616.	52.7	96.9	511.	105.0	47.5	247921.	1306.	1753.
5	799.	53.3	98.0	700.	104.0	45.6	257177.	1341.	1820.
6	1122.	53.3	94.7	1012.	104.0	43.7	265073.	1382.	1900.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00311	77.	1468352.	7.21	324.60	47375.	10.47	1528.
2	.00335	140.	1707181.	6.09	368.62	59319.	12.81	2061.
3	.00354	202.	1840208.	5.45	354.33	67499.	13.00	2476.
4	.00367	267.	1968000.	5.05	354.53	74907.	13.49	2851.
5	.00389	371.	2068555.	4.78	365.70	83374.	14.74	3360.
6	.00422	552.	2146909.	4.53	376.07	93798.	16.43	4098.

TABLE 4.15

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 1400.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 3.9

	F	DT	L	P	TP	X	Q	U	HI
1	262.	50.8	84.0	173.	108.5	58.9	203282.	1112.	1409.
2	389.	51.1	93.6	299.	108.0	52.7	232242.	1263.	1672.
3	506.	52.7	96.9	409.	105.0	49.5	242406.	1277.	1699.
4	616.	53.0	98.0	517.	104.5	47.6	249465.	1307.	1756.
5	799.	53.8	94.7	698.	103.0	45.4	247576.	1278.	1702.
6	1122.	54.4	93.6	1024.	102.0	43.6	255773.	1307.	1758.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00312	77.	1644554.	7.21	303.49	53125.	9.80	1716.
2	.00335	140.	1912042.	6.09	353.57	66437.	12.29	2308.
3	.00354	202.	2061033.	5.45	346.66	75599.	12.72	2773.
4	.00367	267.	2204160.	5.05	355.13	83876.	13.51	3192.
5	.00389	372.	2316781.	4.78	342.01	93429.	13.79	3768.
6	.00422	553.	2404538.	4.53	347.83	105067.	15.20	4591.

TABLE 4.16

EFFECT OF FEED RATE ON HEAT TRANSFER FOR 40 PERCENT GLYCEROL AT N= 1600.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

STEAM PRESSURE= 3.9

	F	DT	E	P	TP	X	Q	U	HI
1	262.	49.4	89.3	171.	111.0	60.7	216716.	1220.	1591.
2	389.	51.6	93.6	297.	107.0	52.7	231255.	1244.	1638.
3	506.	52.7	94.7	403.	105.0	49.2	237584.	1251.	1653.
4	616.	53.3	94.7	513.	104.0	47.3	241354.	1258.	1666.
5	799.	53.6	93.6	701.	103.5	45.3	246338.	1278.	1702.
6	1122.	54.1	92.6	1017.	102.5	43.6	255075.	1310.	1763.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00311	76.	1879491.	7.21	342.80	60527.	11.04	1949.
2	.00335	140.	2185191.	6.09	346.47	75929.	12.04	2638.
3	.00354	202.	2355466.	5.45	337.19	86449.	12.38	3173.
4	.00368	268.	2519040.	5.05	336.90	95926.	12.83	3653.
5	.00389	372.	2647750.	4.78	341.95	106795.	13.79	4308.
6	.00422	553.	2748043.	4.53	348.83	120091.	15.24	5248.

TABLE 4.17

EFFECT OF OVERALL TEMP DIFF FO9 65 PERCENT GLYCE9OL AT N= 1250.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

FEED RATE= 506.

	PS	DT	E	F	TP	X	Q	U	HI
1	2.1	32.4	16.1	487.	111.0	67.1	68360.	587.	648.
2	2.8	39.5	31.2	471.	112.0	69.3	103313.	727.	830.
3	3.5	43.9	40.9	463.	115.0	70.7	129084.	817.	954.
4	4.5	48.8	53.8	448.	119.0	72.7	163168.	930.	1120.
5	5.6	55.7	63.5	441.	120.0	74.3	185821.	928.	1122.

TABLE 4.18

EFFECT OF OVERALL TEMP DIFF FOR 40 PERCENT GLYCEROL AT N=1250.

FEED TEMPERATURE= 90.

VAPOR TEMP,TV= 99.5

FEED RATE= 506.

	PS	DT	E	F	TP	X	G	L	HI
1	1.2	27.3	31.2	461.	102.5	42.6	89533.	912.	1077.
2	2.2	38.1	59.7	441.	103.0	45.4	154371.	1125.	1412.
3	2.8	44.7	73.7	431.	103.0	46.8	185823.	1155.	1472.
4	3.5	50.3	87.2	425.	104.0	48.3	217344.	1201.	1559.
5	4.5	57.1	107.6	388.	104.5	50.8	263858.	1283.	1718.
6	5.6	63.9	124.9	371.	105.5	53.1	303653.	1319.	1800.

TABLE 4.19

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 9.4

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= .4

	F	E	P	Q	U	HI
1	111.	16.8	92.	39084.	1155.	1400.
2	140.	18.1	119.	42298.	1250.	1545.
3	194.	19.4	171.	45783.	1353.	1709.
4	310.	25.8	278.	61585.	1820.	2564.
5	452.	27.1	416.	65989.	1950.	2841.
6	543.	23.3	509.	58184.	1720.	2363.
7	749.	25.8	709.	66181.	1956.	2854.
8	1072.	25.8	1025.	69560.	2056.	3081.
9	1292.	24.5	1242.	68941.	2038.	3038.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00210	120.	4043643.	1.79	198.94	87915.	4.33	1911.
2	.00223	153.	4043643.	1.79	219.56	93337.	5.07	2154.
3	.00243	215.	4043643.	1.79	242.93	101724.	6.11	2559.
4	.00274	348.	4043643.	1.79	364.43	114658.	10.33	3251.
5	.00302	513.	4043643.	1.79	403.78	126381.	12.62	3950.
6	.00316	621.	4043643.	1.79	335.84	132566.	11.91	4346.
7	.00343	862.	4043643.	1.79	405.56	143860.	14.43	5118.
8	.00376	1239.	4043643.	1.79	437.83	157552.	17.06	6139.
9	.00394	1497.	4043643.	1.79	431.78	165171.	17.64	6747.

TABLE 4.20

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250,DT= 16.3

FEED TEMPERATURE= 94.

PRODUCT TEMPRATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= .7

	F	E	P	G	U	HI
1	111.	43.9	66.	100342.	1710.	2410.
2	140.	49.1	89.	112307.	1914.	2857.
3	194.	49.1	142.	112875.	1924.	2880.
4	310.	49.1	256.	114092.	1945.	2929.
5	452.	47.8	396.	112661.	1920.	2871.
6	543.	46.5	486.	110691.	1887.	2794.
7	749.	46.5	689.	112853.	1924	2879.
8	1072.	47.8	1004.	119150.	2031.	3139.
9	1292.	49.1	1218.	124365.	2120.	3368.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00203	104.	4043643.	1.79	342.53	84856.	7.19	1781.
2	.00216	135.	4043643.	1.79	406.05	90431.	9.08	2022.
3	.00238	198.	4043643.	1.79	409.26	99607.	10.08	2454.
4	.00271	334.	4043643.	1.79	416.21	113519.	11.68	3187.
5	.00300	501.	4043643.	1.79	408.05	125630.	12.68	3903.
6	.00315	608.	4043643.	1.79	397.01	131834.	12.94	4298.
7	.00342	849.	4043643.	1.79	409.14	143353.	14.50	5082.
8	.00375	1227.	4043643.	1.79	446.08	157149.	17.34	6107.
9	.00393	1483.	4043643.	1.79	478.67	164774.	19.51	6714.

TABLE 4.21

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 22.0

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.1

	F	S	P	Q	U	HI
1	111.	61.5	46.	147014.	1857.	2783.
2	140.	72.5	66.	164814.	2081.	3353.
3	194.	72.3	119.	165382.	2089.	3373.
4	310.	73.6	232.	169515.	2141.	3520.
5	452.	73.6	371.	171002.	2160.	3574.
6	543.	74.9	458.	174865.	2208.	3718.
7	749.	77.5	658.	182862.	2309.	4033.
8	1072.	69.8	982.	168739.	2131.	3492.
9	1292.	69.8	1197.	171037.	2160.	3575.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00196	92.	4043643.	1.79	395.43	82282.	8.05	1674.
2	.00210	121.	4043643.	1.79	476.56	88053.	10.38	1917.
3	.00234	184.	4043643.	1.79	479.36	97850.	11.60	2368.
4	.00268	320.	4043643.	1.79	500.18	112279.	13.89	3118.
5	.00298	486.	4043643.	1.79	507.87	124671.	15.66	3844.
6	.00313	591.	4043643.	1.79	528.33	130923.	17.11	4239.
7	.00340	831.	4043643.	1.79	573.16	142581.	20.21	5027.
8	.00374	1214.	4043643.	1.79	496.21	156729.	19.23	6075.
9	.00393	1471.	4043643.	1.79	508.05	164437.	20.66	6687.

TABLE 4.22

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 27.0

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.4

	F	E	P	G	U	HT
1	111.	74.9	35.	170351.	1753.	2563.
2	140.	81.1	57.	185233.	1906.	2950.
3	194.	87.5	104.	200386.	2062.	3366.
4	310.	90.4	215.	207437.	2135.	3576.
5	452.	90.4	354.	208924.	2150.	3622.
6	543.	82.7	451.	192368.	1979.	3140.
7	749.	90.4	646.	212033.	2182.	3720.
8	1072.	93.0	960.	221246.	2277.	4024.
9	1292.	93.0	1175.	223544.	2300.	4104.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00193	86.	4043643.	1.79	367.05	80998.	7.34	1618.
2	.00208	116.	4043643.	1.79	419.18	87074.	9.03	1875.
3	.00231	175.	4043643.	1.79	478.29	96624.	11.43	2309.
4	.00266	310.	4043643.	1.79	508.20	111406.	14.00	3069.
5	.00296	476.	4043643.	1.79	514.72	124036.	15.79	3805.
6	.00312	586.	4043643.	1.79	446.19	130671.	14.42	4223.
7	.00340	824.	4043643.	1.79	528.60	142256.	18.60	5005.
8	.00373	1200.	4043643.	1.79	571.87	156258.	22.10	6041.
9	.00392	1457.	4043643.	1.79	583.18	164055.	23.66	6656

TABLE 4.23

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 31.5

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.8

	F	E	P	G	L	HI
1	88.	77.5	10.	175941.	1552.	2174.
2	140.	85.6	53.	193984.	1711.	2516.
3	310.	103.3	203.	236607.	2087.	3493.
4	452.	108.5	337.	249762.	2203.	3856.
5	543.	121.4	413.	279879.	2469.	4833.
6	749.	118.6	618.	276207.	2436.	4701.
7	1330.	116.3	1190.	276456.	2438.	4710.
8	1395.	112.4	1257.	268381.	2367.	4432.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00174	57.	4043643.	1.79	308.89	73100.	5.58	1321.
2	.00207	116.	4043643.	1.79	357.61	86644.	7.66	1857.
3	.00264	302.	4043643.	1.79	496.43	110721.	13.59	3032.
4	.00294	466.	4043643.	1.79	547.92	123341.	16.71	3762.
5	.00309	564.	4043643.	1.79	686.78	129389.	21.98	4140.
6	.00338	807.	4043643.	1.79	668.03	141533.	23.38	4954.
7	.00394	1489.	4043643.	1.79	669.28	164942.	27.30	6728.
8	.00399	1567.	4043643.	1.79	629.87	167057.	26.02	6902.

TABLE 4.24

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 35.4

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 2.1

	F	E	P	G	L	HI
1	115.	108.5	6.	246234.	1933.	3095.
2	185.	118.8	65.	270300.	2121.	3648.
3	360.	115.0	241.	263388.	2067.	3480.
4	624.	120.1	494.	277813.	2180.	3839.
5	851.	121.4	715.	283109.	2222.	3979.
6	1155.	121.4	1013.	286286.	2247.	4066.
7	1444.	114.3	1303.	273270.	2145.	3722.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00184	71.	4043643.	1.79	439.79	77090.	8.38	1470.
2	.00221	147.	4043643.	1.79	518.39	92398.	11.85	2111.
3	.00275	354.	4043643.	1.79	494.58	115214.	14.09	3283.
4	.00321	660.	4043643.	1.79	545.50	134576.	18.15	4479.
5	.00350	925.	4043643.	1.79	565.44	146440.	20.48	5303.
6	.00379	1280.	4043643.	1.79	577.75	158834.	22.69	6239.
7	.00402	1623.	4043643.	1.79	528.94	168538.	22.05	7025.

TABLE 4.35

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 39.1

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 2.5

	F	E	P	Q	U	HI
1	111.	103.3	8.	234525.	1666.	2456.
2	140.	111.1	28.	252325.	1793.	2759.
3	210.	135.6	171.	309533.	2199.	3955.
4	452.	139.5	306.	319771.	2272.	4216.
5	543.	139.5	395.	320717.	2279.	4241.
6	749.	148.5	589.	343299.	2439.	4888.
7	1072.	142.1	911.	332094.	2360.	4554.
8	1292.	139.5	1129.	328557.	2335.	4454.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00183	70.	4043643.	1.79	349.08	76676.	6.62	1454.
2	.00200	98.	4043643.	1.79	392.01	83599.	8.10	1728.
3	.00260	283.	4043643.	1.79	562.06	108949.	15.14	2935.
4	.00291	447.	4043643.	1.79	599.14	120122.	18.09	3688.
5	.00307	553.	4043643.	1.79	602.70	128778.	19.19	4101.
6	.00336	790.	4043643.	1.79	694.57	140764.	24.18	4900.
7	.00371	1171.	4043643.	1.79	647.21	155345.	24.86	5968.
8	.00390	1430.	4043643.	1.79	633.01	163284.	25.56	6593.

TABLE 4.26

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 42.5

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 49.0

STEAM PRESSURE= 2.8

	F	E	P	G	L	HI
1	111.	108.5	3.	246194.	1609.	2343.
2	140.	142.1	40.	322334.	2107.	3687.
3	194.	146.5	44.	337487.	2206.	4027.
4	310.	144.7	162.	329952.	2157.	3854.
5	452.	148.5	297.	340190.	2224.	4091.
6	543.	149.8	385.	344054.	2249.	4184.
7	749.	147.3	550.	340382.	2225.	4095.
8	1072.	155.0	899.	361264.	2362.	4627.
9	1292.	149.8	1119.	351894.	2300.	4379.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00181	67.	4043643.	1.79	333.02	75829.	6.25	1422.
2	.00190	80.	4043643.	1.79	523.97	79440.	10.29	1561.
3	.00213	140.	4043643.	1.79	572.23	91308.	12.92	2062.
4	.00259	278.	4043643.	1.79	547.70	108437.	14.69	2908.
5	.00291	442.	4043643.	1.79	581.31	121759.	17.50	3666.
6	.00307	547.	4043643.	1.79	594.54	128425.	18.88	4079.
7	.00336	791.	4043643.	1.79	581.96	140798.	20.26	4903.
8	.00370	1164.	4043643.	1.79	657.49	155094.	25.22	5949.
9	.00389	1424.	4043643.	1.79	622.37	163111.	25.10	6580.

TABLE 4.27

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1250.DT= 45.7

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 5.2

	F	E	P	G	[illegible]	HI
1	111.	111.1	.	252028.	1532.	2187.
2	140.	142.1	0.	322334.	1960.	3259.
3	194.	147.3	46.	334570.	2034.	3486.
4	310.	152.4	154.	347455.	2112.	3741.
5	452.	162.8	284.	372278.	2263.	4286.
6	543.	167.9	367.	384892.	2340.	4594.
7	749.	160.2	577.	369553.	2247.	4222.
8	1072.	167.9	886.	390434.	2374.	4738.
9	1292.	162.8	1106.	381064.	2317.	4498.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00180	65.	4043643.	1.79	310.84	75394.	5.80	1406.
2	.00190	80.	4043643.	1.79	463.19	79440.	9.10	1561.
3	.00218	141.	4043643.	1.79	495.38	91431.	11.20	2067.
4	.00258	274.	4043643.	1.79	531.63	107992.	14.20	2884.
5	.00289	434.	4043643.	1.79	609.04	121183.	18.25	3632.
6	.00305	537.	4043643.	1.79	652.89	127799.	20.63	4039.
7	.00335	783.	4043643.	1.79	599.99	140460.	20.84	4879.
8	.00370	1156.	4043643.	1.79	673.25	154841.	25.78	5929.
9	.00389	1416.	4043643.	1.79	639.23	162894.	25.75	6562.

TABLE 4.28

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1600.DT= 22.0

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.1

	F	E	P	G	U	HI
1	111.	51.7	58.	117844.	1488.	2007.
2	140.	56.8	81.	129810.	1639.	2305.
3	194.	54.3	137.	124543.	1573.	2170.
4	310.	56.6	248.	131594.	1662.	2351.
5	452.	62.0	382.	144749.	1828.	2716.
6	543.	59.4	473.	139861.	1766.	2576.
7	749.	62.0	673.	147858.	1867.	2808.
8	1072.	58.1	994.	142486.	1799.	2650.
9	1292.	59.4	1208.	147701.	1865.	2803.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00200	99.	5175864.	1.79	285.24	107416.	5.92	2229.
2	.00214	130.	5175864.	1.79	327.50	114764.	7.26	2545.
3	.00237	195.	5175864.	1.79	308.44	127007.	7.57	3117.
4	.00270	330.	5175864.	1.79	334.13	144809.	9.35	4051.
5	.00299	493.	5175864.	1.79	385.95	160135.	11.94	4954.
6	.00314	600.	5175864.	1.79	366.07	168221.	11.90	5467.
7	.00341	840.	5175864.	1.79	399.01	182999.	14.11	6470.
8	.00375	1221.	5175864.	1.79	376.65	200894.	14.62	7797.
9	.00393	1477.	5175864.	1.79	398.34	210695.	16.22	8577.

TABLE 4.29

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1600.DT= 27.0

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.4

	F	E	P	G	U	HI
1	111.	77.5	33.	176185.	1813.	2722.
2	140.	80.1	58.	182316.	1876.	2875.
3	194.	80.1	111.	182884.	1882.	2889.
4	310.	80.1	225.	184100.	1894.	2920.
5	452.	77.5	367.	179753.	1850.	2810.
6	543.	82.7	451.	192368.	1979.	3140.
7	749.	77.5	658.	182862.	1882.	2889.
8	1072.	77.5	975.	186242.	1916.	2976.
9	1292.	77.5	1190.	188540.	1940.	3037.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00192	85.	5175864.	1.79	386.85	103093.	7.71	2053.
2	.00208	116.	5175864.	1.79	408.53	111636.	8.81	2408.
3	.00232	180.	5175864.	1.79	410.59	124471.	9.87	2993.
4	.00267	316.	5175864.	1.79	415.02	143291.	11.49	3967.
5	.00297	484.	5175864.	1.79	399.35	159393.	12.30	4909.
6	.00312	586.	5175864.	1.79	446.19	167259.	14.42	5405.
7	.00340	831.	5175864.	1.79	410.51	182504.	14.47	6435.
8	.00374	1209.	5175864.	1.79	422.91	200426.	16.38	7761.
9	.00392	1466.	5175864.	1.79	431.52	210317.	17.53	8546.

TABLE 4.30

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1600.DT= 31.5

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.8

	F	E	P	G	U	HI
	111.	90.4	20.	205355.	1811.	2752.
2	140.	94.3	44.	214404.	18[illegible].	2951.
3	194.	95.6	96.	217888.	1922.	3031.
4	310.	98.2	208.	224939.	1984.	3199.
5	452.	95.6	349.	220592.	1946.	3094.
6	543.	95.6	438.	221538.	1954.	3117.
7	749.	95.6	641.	223701.	1973.	3169.
8	1072.	90.4	963.	215412.	1900.	2974.
9	1292.	90.4	1177.	217710.	1920.	3027.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00188	77.	5175864.	1.79	391.06	100710.	7.61	1960.
2	.00204	106.	5175864.	1.79	419.41	109587.	8.88	2320.
3	.00229	171.	5175864.	1.79	430.77	122871.	10.23	2917.
4	.00265	305.	5175864.	1.79	454.54	142075.	12.48	3900.
5	.00296	473.	5175864.	1.79	439.75	158514.	13.47	4855.
6	.00311	579.	5175864.	1.79	442.94	166717.	14.27	5370.
7	.00339	821.	5175864.	1.79	450.29	181920.	15.83	6394.
8	.00373	1202.	5175864.	1.79	422.67	200112.	16.34	7737.
9	.00392	1459.	5175864.	1.79	430.18	210045.	17.46	8524.

TABLE 4.31

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 1600.DT= 35.4

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 2.1

	F	E	P	G	U	HI
1	111.	103.5	8.	234525.	1841.	2853.
2	140.	108.5	30.	246491.	1975.	3100.
3	194.	111.0	81.	252893.	1985.	3240.
4	310.	111.1	195.	254109.	1994.	3267.
5	452.	113.7	332.	261430.	2052.	3434.
6	543.	108.5	425.	250708.	1968.	3191.
7	749.	108.5	628.	252871.	1985.	3239.
8	1072.	113.7	939.	267919.	2103.	3589.
9	1292.	108.5	1160.	258548.	2029.	3367.

	DF	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00183	70.	5175864.	1.79	405.49	98146.	7.69	1861.
2	.00200	99.	5175864.	1.79	440.56	107416.	9.14	2229.
3	.00226	162.	5175864.	1.79	460.38	121207.	10.78	2838.
4	.00263	298.	5175864.	1.79	464.23	141188.	12.66	3851.
5	.00294	463.	5175864.	1.79	488.03	157620.	14.86	4800.
6	.00310	571.	5175864.	1.79	453.53	166171.	14.56	5335.
7	.00338	816.	5175864.	1.79	460.31	181500.	16.14	6365.
8	.00372	1188.	5175864.	1.79	510.07	199543.	19.66	7693.
9	.00391	1448.	5175864.	1.79	478.52	209663.	19.38	8493.

TABLE 4.32

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 600.DT= 16.3

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= .7

	F	E	P	Q	U	HI
1	111.	19.4	90.	44918.	766.	868.
2	140.	23.3	114.	53967.	920.	1075.
3	194.	25.8	165.	60368.	1029.	1231.
4	310.	28.4	276.	67419.	1149.	1411.
5	452.	36.2	408.	86408.	1473.	1951.
6	543.	38.8	494.	93188.	1588.	2167.
7	749.	38.8	696.	95351.	1625.	2239.
8	1072.	36.2	1015.	92896.	1583.	2158.
9	1292.	34.9	1232.	92277.	1573.	2137.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00209	119.	1940949.	1.79	123.33	42066.	2.67	912.
2	.00222	150.	1940949.	1.79	152.80	44578.	3.51	1024.
3	.00242	212.	1940949.	1.79	174.87	48612.	4.38	1218.
4	.00273	340.	1940949.	1.79	200.48	54976.	5.68	1557.
5	.00301	508.	1940949.	1.79	277.30	60506.	8.64	1886.
6	.00315	612.	1940949.	1.79	307.98	63398.	10.06	2071.
7	.00343	854.	1940949.	1.79	318.18	68901.	11.30	2446.
8	.00376	1233.	1940949.	1.79	306.62	73533.	11.93	2939.
9	.00394	1491.	1940949.	1.79	303.75	79202.	12.39	3232.

TABLE 4.33

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 600.DT= 22.0

FEED TEMPERATURE= 94..

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.1

	F	E	P	Q	U	HI
1	111.	46.5	63.	106176.	1341.	1741.
2	140.	43.9	94.	100639.	1271.	1621.
3	194.	56.5	134.	130377.	1646.	2319.
4	310.	68.5	237.	157847.	1993.	3120.
5	452.	69.8	375.	162251.	2049.	3266.
6	543.	67.2	466.	157363.	1987.	3104.
7	749.	67.2	668.	159526.	2015.	3175.
8	1072.	64.6	987.	157071.	1984.	3094.
9	1292.	64.6	1203.	159369.	2013.	3169.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00202	103.	1940949.	1.79	247.36	40583.	5.17	849.
2	.00217	138.	1940949.	1.79	230.41	43649.	5.18	982.
3	.00236	193.	1940949.	1.79	329.60	47535.	8.07	1164.
4	.00269	323.	1940949.	1.79	443.32	54021.	12.34	1504.
5	.00299	468.	1940949.	1.79	464.10	59912.	14.33	1849.
6	.00313	596.	1940949.	1.79	441.09	62963.	14.31	2042.
7	.00341	837.	1940949.	1.79	451.15	68563.	15.94	2422.
8	.00374	1217.	1940949.	1.79	439.75	75277.	17.05	2919.
9	.00393	1474.	1940949.	1.79	450.41	78970.	18.33	3213.

TABLE 4.34

EFFECT OF FEED RATE ON HEAT TRANSFER FOR WATER AT N= 600.DT= 27.0

FEED TEMPERATURE= 94.

PRODUCT TEMPERATURE= 99.

VAPOR TEMP,TV= 99.0

STEAM PRESSURE= 1.4

	F	S	P	G	U	HI
1	111.	64.5	46.	147014.	1513.	2076.
2	140.	68.5	70.	156063.	1566.	2264.
3	194.	80.1	111.	182884.	1832.	2889.
4	310.	82.1	223.	189935.	1954.	3074.
5	452.	85.3	359.	197256.	2030.	3276.
6	543.	86.5	447.	201119.	2070.	3387.
7	749.	85.3	661.	200364.	2062.	3365.
8	1072.	82.7	970.	197910.	2036.	3294.
9	1292.	81.4	1186.	197291.	2030.	3277.

	DE	RE	RE2	PR	NU2	RE1	NU	RE3
1	.00196	92.	1940949.	1.79	295.06	39495.	6.00	804
2	.00211	126.	1940949.	1.79	321.70	42462.	7.04	929.
3	.00232	180.	1940949.	1.79	410.59	46677.	9.87	1122.
4	.00267	314.	1940949.	1.79	436.82	53670.	12.08	1484.
5	.00297	479.	1940949.	1.79	465.53	59632.	14.30	1832.
6	.00312	584.	1940949.	1.79	481.33	62661.	15.54	2023.
7	.00340	827.	1940949.	1.79	478.21	68345.	16.84	2407.
8	.00374	1206.	1940949.	1.79	468.17	75113.	18.12	2907.
9	.00392	1464.	1940949.	1.79	465.67	78838.	18.91	3202.